DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES

PART III: DEVELOPING CRITICAL TECHNOLOGIES

SECTION 16: POSITIONING, NAVIGATION, AND TIME TECHNOLOGY

October 1999 (updated May 2000)

Defense Threat Reduction Agency
Dulles, VA

SECTION 16—POSITIONING, NAVIGATION, AND TIME TECHNOLOGY

Scope

Highlights

- Positioning, navigation, and time (PNT) technology usage has doubled every 5 years, mostly because of the U.S. Global Positioning System (GPS) program and the miniaturization of electromechanical components. Future PNT usage is expected to double every 2 years because of telecommunication and automobile navigation commercial markets. On 1 May 2000, the President discontinued Selective Availability of GPS. "*The decision to discontinue Selective Availability is the latest measure in an ongoing effort to make GPS more responsive to civil and commercial users worldwide. This increase in accuracy will allow new GPS applications to emerge and continue to enhance the lives of people around the world.*"[1]
- The economic engine for PNT is both the nonmilitary commercial community sector and the expanding need for more accurate position and especially precise time.
- Military exploitation and harnessing of a three-dimensional position (latitude, longitude, and altitude) and precise time (POSITIME) common battlespace grid reference and use of hybrid multisensor arrays are in the embryonic stage. The impact on the military in terms of situational awareness—that is, the use of multiple sensor data to reduce fratricide and positively identify friendly forces, foe targets, and neutrals—will be significant.
- Significant advances in PNT technologies should be anticipated from developed nations and less developed nations. This will allow more nontraditional sources in manufacture of PNT products.

OVERVIEW

Recent localized conflicts and the evolving role of the U.S. military in antiterrorism points to (1) the future use of more autonomous unmanned vehicles (AUVs) for precision strike and tactical combat, in addition to surveillance, targeting, and covert operations, and (2) more use of long-range, stand-off, precision and laser-guided weapons and other smart weapons, including artillery shells and munitions. Joint U.S. and allied military land, air, and sea forces will also need new levels of situational awareness to reduce fratricide and provide rapid battlefield tracking of troops, both friend and foe. The need to minimize time over target and maximize kill will require accurate and continuous knowledge and location of targets, especially mobile targets, rapid battlefield damage assessment, and in-flight retargeting of missiles and weapons. These capabilities will translate directly into tactical and strategic military

[1] President Bill Clinton, the White House

advantage, saved lives, and reduced military cost. To achieve this will require using advanced technologies in computer processing, navigation and precise time, telecommunications, and positive combat identification sensors in a "system of systems." This will provide the capability to determine accurate locations of friendly and enemy forces, as well as to collect, process, and distribute relevant data that is position and time (POSITIME) tagged across the battlespace. This interactive "tactical picture" will gain U.S. forces an enormous dominant battlespace awareness, which will decrease response time and make the battlespace considerably transparent for the warfighter.[2] Included in this section are descriptions of the technologies necessary to achieve dominant battlespace awareness, including autonomous and cooperative positioning, data-based navigation systems, positive combat identification, and nonintrusive detection of military force elements. Figures 16.0-1 and 16.0-2 show battlespace awareness for two warfare scenarios: sophisticated conventional warfare and military operations in urban terrain, respectively. The latter is the more complex and resource-intensive environment; it requires very precise situational awareness.

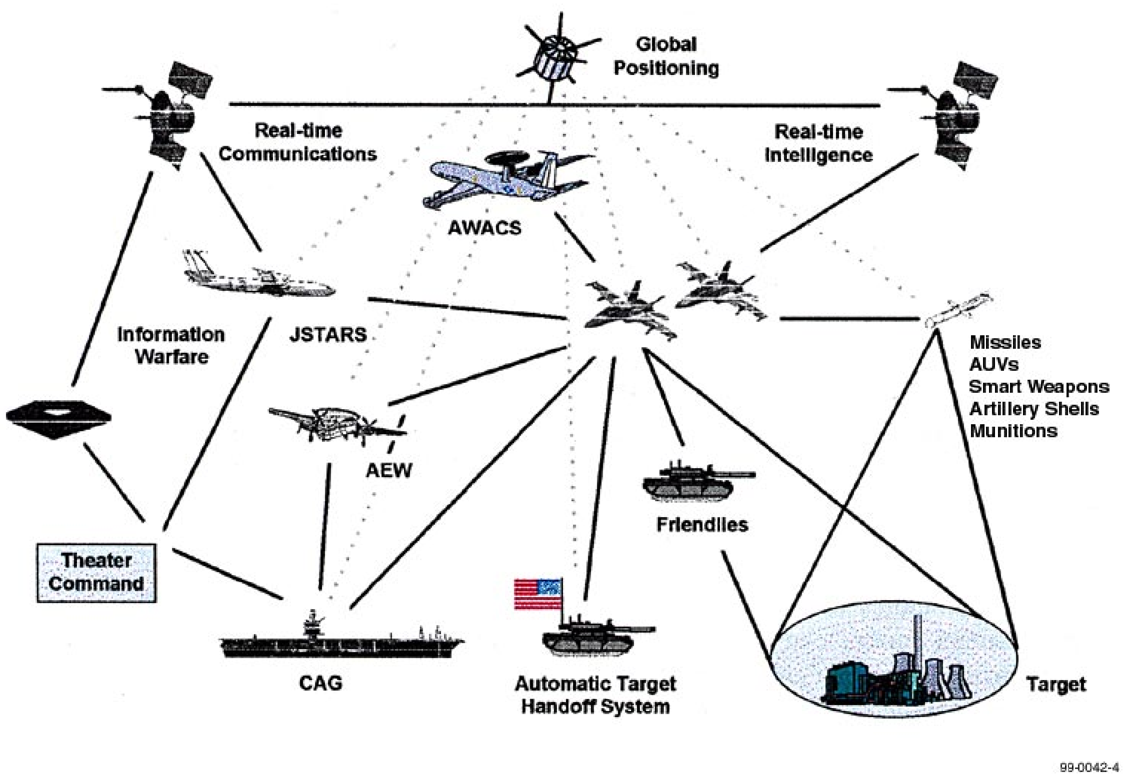

Figure 16.0-1. Concept—Sophisticated Conventional Warfare

RATIONALE

The importance of these technologies and their potential capabilities could be used (by friend and foe) to deliver conventional weapons, a single item (for nuclear), individually targeted remote vehicles (RVs), or a set of items to a level of accuracy appropriate to the destructive footprint of these munitions. These parameters could be achieved either individually or when used as an integrated or hybrid system. Accurate positioning, attitude, pointing, and control of land, sea, air, and space vehicles are essential for effective coordination of highly mobile military forces. These capabilities directly enhance the delivery accuracy and lethality of manned and unmanned guided and unguided weapons systems. In addition, other mission requirements, such as reconnaissance and detection, require accurate

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[2] *Joint Vision 2010.*

velocity, motion compensation, and positioning synchronization data to maintain real-time knowledge of the enemy. Accurate POSITIME sequencing and use of sensor information are key force multipliers to offset numerical superiority of an adversary and reduce casualties. Access to these technologies would amplify threats to regional stability by making available to hostile forces a much superior capability.

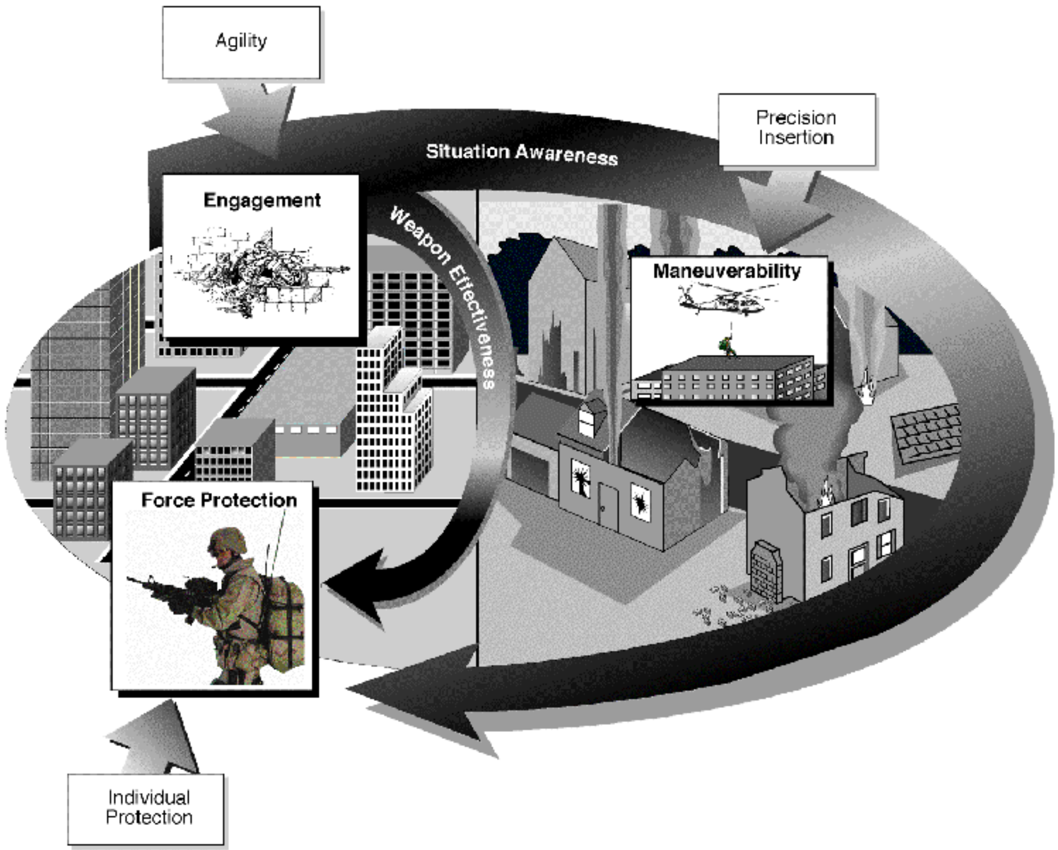

Figure 16.0-2. Concept—Military Operations in Urban Terrain

Situational awareness greatly reduces the combat stress of the warfighter. Situational awareness is a fundamental requirement for combat decision making and fratricide reduction. U.S. forces must be able to positively identify all targets in the battlespace for all combat mission areas—air to air, air to surface, surface to surface, and surface to air. Surface, in this case, includes land, sea, and subsurface. Combat identification (CID) is essential in order for commanders to effectively field fighting forces that can rapidly and positively identify enemies, friends, and neutrals in the battlespace; manage and control the battle area; optimally employ weapons and forces; and minimize the risk and occurrence of fratricide.[3]

The greatly expanded military use of the U.S. GPS has created the significant, military advantage of an accurate navigation and time reference system, but at the price that hostile forces will try to locally jam GPS signals or use GPS for their own purposes. The latter could also require the use of local jamming by friendly forces to deny use of GPS by an enemy. Either scenario will require U.S. forces and its allies to use GPS in a high jamming environment. Developing technologies for GPS antijam improvements will mitigate this issue until new developing technologies provide DoD with an affordable, nonjammable, equivalent GPS precision navigation and precise time

[3] *Joint Warfighting Science and Technology Plan: Combat Identification.*

reference for the battlespace. In urban areas, loss of GPS signals due to signal blockage and multipath problems provides a challenge to overcome.

TECHNOLOGY ASSESSMENT

Over the next 2 to 5 years, differential GPS (DGPS) systems will provide very accurate navigation within 1–2 m in localized areas. Wide-area augmentation systems (WAAS) for air traffic control purposes will provide differential corrections over a wider area than most DGPS. Local area augmentation system (LAAS) will provide differential corrections for air traffic control in the vicinity of an airport. The use of GPS, long-range aid to navigation (LORAN), and other navigation/telecommunication systems [(Russian) Global Navigation Satellite System (GLONASS), European Geostationary Navigation Overlay Service (EGNOS), European Union GNSS-2, Teledesic, and other satellite telecommunication systems] will provide greater accuracy and minimize loss of satellite signals. Continued improvements in orbit accuracy and time could further improve GPS accuracy from 2–3 m to 1.5 m and DGPS accuracy to less than 0.6 m. However, radio navigation systems are not completely autonomous, relying on external signals that can be jammed. The military application of geodetic and geophysical databases, such as terrain, magnetic, and gravity matching techniques, offers the possibility of a more autonomous navigation capability, reducing the concern for detection and jamming of GPS and other radio aids. Such geodetic and geophysical data bases can support navigation to near-GPS accuracy when GPS service is not available (see subsection 16.3). Commercial telecommunications growth will continue, providing affordable hand-held cellular communications worldwide, including GPS/digital maps at the local area. On May 1, 2000, with the discontinuance of Selective Availability, the civilian accuracy of GPS was reduced (improved) to less than 10 meters and the accuracy of time broadcast by GPS was improved to within 40 billionths of a second[4]. By 2001, the Federal Communications Commission (FCC) has mandated that all cellular phones identify their locations to within 125 m for 911 emergency calls. These decisions will significantly increase PNT usage and research investments. Hybrid inertial navigation system (INS) systems, such as GPS combined with ring laser gyroscope (RLG) or fiber-optic gyroscope (FOG) INS, will be expanded with more combinations of navigation and telecommunication functions. This will minimize the effect of GPS jamming and loss of satellite signals due to terrain or other reasons. Miniaturized GPS (GPS on a chip) will hasten hybrid INS/telecommunication applications at reduced cost (see subsection 16.1.). Maximum utilization of near and far infrared devices (i.e., thermal tapes, BUDD, and Phoenix Light) and image intensifier (I2) devices across U.S. forces, together with increased training, can provide limited improvements in CID. Further integration among the U.S. forces and its allies of new CID technologies, both cooperative and noncooperative, will present a challenge to ensure that they are reliable and affordable.

Over the next 5 to 15 years INS could be revolutionized by microelectromechanical systems (MEMS) technology, a fabrication approach that conveys the advantages of miniaturization, multiple components, and microelectronics to the design and construction of integrated electromechanical systems. Current MEMS tuning fork gyroscopes, smaller than a paper clip, have an accuracy of 100 deg/hr, with 10 deg/hr accuracy expected by the end of 1999. Given similar experiences over the past 20 years with RLGs and FOGs, it is very likely that MEMS gyroscopes with accuracy of 0.1 deg/hr are achievable within the next 5 to 15 years, with further improvements thereafter. Concurrently, RLG and FOG aircraft INS performance could continue to improve from 1.0 to 0.1 nmph circle error probable (CEP). MEMS technology could be further enhanced by the continued growth of optical computing/processing/correlating technologies (see Section 10), especially in georegistration of hybridized data from remote sensors (pseudo-imaging) using highly accurate timing data. The use of MEMS technology within RLG/FOG INS is very possible as part of the affordable INS technology evolution shown in subsection 16.1. Accurate and miniaturized “smart” gravity and magnetic detection sensors combined with GPS/INS and satellite communications will provide target recognition and real-time movement and direction of enemy forces and large mass items, such as missiles, tanks, and other large weapons. These same sensors combined with biological, chemical, and/or neutron emission sensors could help identify and track movement of biological, chemical, and nuclear emissions on the battlefield. Further cost reductions would allow localized battle areas to be “seeded” (by mini-AUVs) with these detection devices, providing critical intelligence of troop, missile, tank, and artillery movement. Accurate time,

[4] White House, Office of Press Secretary

combined with multiple optical, vibration, magnetic, and gravity sensors in smart arrays, is a leveraging application of these technologies. The use of a standard time reference with ion clock technology will improve absolute accuracy to better than 10^{-15}. Further microminiaturization of low-power clock technologies will provide autonomous "fly-wheel" time devices in all navigation and communication equipment, providing direct-Y code acquisition and minimizing the effect of GPS jamming. These improvements will result in a precise standard military time reference for U.S. forces and its allies, providing enormous benefits in precision navigation and rapid and secure communications across the battlespace. Because of its importance, precise time and frequency (PT&F) capabilities are discussed in a separate subsection (16.5).

The use of GPS time synchronization to locate the position of 911 cellular users can be adapted by the military to improve situational awareness in urban terrain. Integrated with CID tags and localized terrain maps, mini-navigation/low probability of interception (LPI) telecommunication sensors may provide positive ID of friendly forces and thereby reduce the "fog of war" in urban terrain. Radio frequency identification (RFID) is a leveraging technology. Improvements in the land warrior system, the U.S. Army's first-generation integrated fighting system for dismounted combat soldiers, will integrate telecommunications and navigation technologies with an integrated helmet assembly subsystem including a heads-up display and image intensifier for night operations, a weapons subsystem with thermal weapon sight, close combat optics, video camera with a video capture capability, laser rangefinder/digital compass, and an infrared laser-aiming light.

Over the next 15 to 20 years nanoelectromechanical systems (NEMS) technology, a technique of building machines (such as accelerometers and gyroscopes) from individual atoms and molecules, could continue to decrease the size and cost of INS. The low manufacturing cost of this technology could further revolutionize navigation by providing an autonomous INS using multiple NEMS accelerometers (potentially eliminating the need for gyroscopes), at a cost of less than $500. For the military, this could affordably allow a nonjammable INS to be installed on every air, land, and sea vehicle; smart weapon; artillery shell; and warfighter. Integrated with assets, such as the Airborne Warning and Control System (AWACS), satellites, and AUVs, using advanced electro-optics, infrared radar, video cameras, motion-detection sensors, and sophisticated automatic target-identification algorithms and data bases, this technology will provide a very accurate view of the battlespace, particularly during military operations in urban terrain (MOUT) (see Figure 16.0-2). Expanded use of an affordable, accurate, and autonomous navigation system could better support precision insertion of combat forces and their protection, providing low fratricide and collateral damage, particularly in urban terrain. By 2025, friendly troops and equipment will enter the battlespace with their personal identifiers. The identification mechanisms could be in the form of microchips worn by or imbedded in the soldiers. The same principle could be applied to vehicles. NEMS technology promises to be among the most promising developments of the 21st century.

WORLDWIDE TECHNOLOGY ASSESSMENT

Depending on national desires and needs, nations have chosen to develop, produce, and use positioning, navigation, and PT&F technologies for military and commercial purposes. Many countries do not have an indigenous aircraft-, ship-, or spacecraft-manufacturing capability and the inherent guidance and navigation technology that are fundamental requirements. The cost for Third World countries to design, fabricate, and apply these technology areas has been a limiting proliferation factor. However, the latest transition of MEMS technology to low cost and highly accurate gyroscopes and accelerometers, coupled with advances in computer memory and speed, have significantly reduced the cost of INS. Historically, an INS was and continues to be more expensive to produce and maintain than a radio navigation system. This and other military mission considerations have led many nations to rely more on radio navigation systems for many military and commercial needs. Continuous gains in microminiaturization of sensors and computer technology will continue to drive down the cost of INS. As INS costs drop, the technology could become available to countries heretofore unable to afford this system, which has the military advantage of an autonomous, covert, and nonjammable guidance and navigation capability for aircraft, missiles, and weapons of mass destruction (WMD).

MEMS technology is already used by Japan, South Korea, and other countries for automotive airbag applications (accelerometers) and ride control and antiskid systems (gyroscopes and accelerometers). Current MEMS technology has been successful in producing accurate linear acceleration sensors, but is years away from providing an accuracy similar to a RLG INS. However, low-cost MEMS INS, compounded with the worldwide commercial use of global navigation satellite systems (GNSS) and its technology advances and the emergence of accurate terrain mapping, will allow for the proliferation and accessibility of highly accurate PNT systems, which will be a challenge to prevent. Currently, the only GNSS that exist are the U.S. GPS and the GLONASS. A regional GNSS, such as the European Union GNSS 2, is a strong possibility. The GNSS 2 may consist of 63 low-Earth-orbiting satellites, providing 5- to 10-m accuracy. The latest satellite-based cellular phone systems could also solve the geolocation problem. Increased proliferation of foreign GNSS capability could provide unbridled and accessible navigation accuracy that could enhance the delivery accuracy of Third World countries' missiles and WMD.

The radio navigation process supports a magnetic heading reference for the world. The expanding use of GPS has reversed this trend, and the future will see the conversion to true heading for geo-referencing as mapping and imaging technologies converge. Many countries are using the U.S. GPS to improve the accuracy of their weapons and the situational awareness of their operations forces. Jamming of GPS signals by the United States in the event of war would limit its usefulness to an adversary, but doing so would require the United States and its friendly forces to operate effectively in a high jamming environment. Those developing technologies such as accurate, small clocks that allow usability of GPS signals in a high jamming environment are considered critical for military use. Currently, U.S. military needs for crypto, secure telecommunications, and antijam communications are becoming increasingly dependent on the accurate time from GPS. Precise time is key to the future of navigation and communication systems. The need for an autonomous, nonjammable, common time reference source is discussed in subsection 16.5. Precise time technologies will provide accurate and stable time to be disseminated to military forces around the world. The United States has been the world leader in the development and utilization of precise time technology, including telecommunication, encryption, and data transfer.

Some countries, such as France, the UK, and Russia, have been leaders in positioning, including inertial, gravity, and magnetic sensors; radio navigation; and precise time because of their indigenous aircraft and spacecraft industry. These countries have developed their own technologies. For other countries, much of the technology capability has been obtained through U.S. licensing agreement transfers and foreign students attending U.S. universities. Now, however, inertial and GNSS technology symposia are held in Europe, Russia, and China with wide international attendance and paper presentations. Hybrid navigation system technology is also now a common topic at international navigation conferences, and the theory and practice of Kalman filters is well known. Continued cooperation with allies and international bodies is necessary to reduce the proliferation and use of accurate INS, hybrid INS, and GNSS capabilities for use by adversaries in missiles and WMD.

The development leaders of situational awareness/combat identification (SA/CID) technologies are for the most part located within the NATO countries: France, Germany, the UK, and the United States. Further details of the foreign technology assessment are provided in the respective subsections.

Country	Sec. 16.1 Inertial Navigation and Related Components	Sec. 16.2 Gravity Meters and Gravity Gradiometers	Sec. 16.3 Radio and Data-Based Referenced Navigation Systems
Australia	●●	●●●	●●
Austria	●	●●●	●
Brazil	●	●●●	●●
Canada	●●●●	●●●	●●●●
China	●●●	●●●●	●●●
Czech Republic	●	●●●	●
Finland	●	●●●	●●
France	●●●●	●●●●	●●●●
Germany	●●●●	●●●	●●●
Hungary	●	●●	●
India	●●●	●●	●●●
Israel	●●●●	●●	●●●●
Italy	●●●	●●●●	●●●
Japan	●●●	●●●●	●●●●
Netherlands	●●	●●	●●●
Poland	●	●●	●●
Romania	●	●●	●
Russia	●●●●	●●●●	●●●●
Slovak Republic	●	●●	●
South Africa	●●●	●	●●●
South Korea	●●	●	●●●
Spain	●●	●	●●
Sweden	●●	●●●	●●
Switzerland	●●	●●●	●●
Taiwan	●●	●	●●
UK	●●●●	●●●	●●●●
Ukraine	●●●●	●●	●●●●
United States	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

(Continued)

Figure 16.0-3. Positioning, Navigation, and Time WTA Summary

Country	Sec. 16.4 Magnetometer and Magnetic Gradiometers	Sec. 16.5 Precision Time and Frequency	Sec. 16.6 Situational Awareness/ Combat Identification
Australia	●●	●●	●●●
Austria	●●	●●	●●
Brazil	●	●●	
Canada	●●●●	●●●	●●●
China	●●	●●●	●●
Czech Republic	●	●●	
Finland	●●	●●	●
France	●●●	●●●●	●●●●
Germany	●●●	●●●●	●●●●
Hungary	●●	●●	
India	●	●●	
Israel	●●	●●●	●●●
Italy	●●	●●●	●●●
Japan	●●●	●●●	●●●
Netherlands	●●	●●	
Poland	●	●●	
Romania	●	●●	
Russia	●●●●	●●●●	●●●
Slovak Republic	●	●●	
South Africa	●●	●●●	
South Korea	●●	●●●	●●
Spain	●	●●	
Sweden	●●	●●	●●
Switzerland	●●	●●●	●●
Taiwan	●	●●	
UK	●●●	●●●●	●●●●
Ukraine	●●	●●●	●●
United States	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.0-3. Positioning, Navigation, and Time WTA Summary (Cont'd)

SECTION 16.1—INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

Highlights

- Inertial navigation technologies provide an autonomous, covert, and nonjammable three-dimensional position and velocity reference for land, sea, and space platforms, which will enhance the ability of the military to achieve mission goals.
- Major reduction in manufacturing complexity, size, and cost of INS will be realized by use of MEMS sensors, electronics, and radio-frequency (RF) interfaces. This will allow expanded military use of INS (for personnel, low- cost vehicles, smart artillery and ordnance, and AUVs) and expanded commercial applications, thereby providing a larger market for more nontraditional manufacturers of inertial navigation technology.
- Through better noise compensation techniques, RLG and FOG will continue to improve free inertial performance (1.0 to 0.1 nm/hr), providing better platform stability augmentation and weapon delivery.
- Future developments in nanotechnology, particularly NEMS accelerometers, may eliminate the need for gyroscopes if quantum noise measurement techniques are resolved. If achieved, this may exploit the use of NEMS within the basic building materials for tanks, vehicles, and uniforms, significantly improving situational awareness and reducing fratricide.
- Military application of INS with embedded GPS, LORAN, and data-based referenced navigation systems (DBRNS) will increase. These hybrid systems bound the time-dependent errors of the inertial gyroscopes. The resulting accuracy of position and time provides a more robust navigation system. Improvements in hybrid systems will lead to port-to-port submarine navigation without need to surface.
- Built-in redundancy through low cost, small size, lightweight, and highly reliable components will allow an affordable, throwaway logistics concept. This will enable a rapid affordable technology insertion of INS technology.

OVERVIEW

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and command, control, and communications (C3) systems require high navigation accuracy. Figures 16.1-1 and 16.1-2 address the key gyroscope and accelerometer performance requirements for these military applications, as well the key commercial automotive market driver. INS technology has been enormously affected by advances in computer technology (memory and throughput), sensors, power quality, and electronics. Most current INS use optical gyroscopes: RLG or FOGs. RLG and FOG INS technology will continue to improve free inertial sensor performance from 1.0 nmph to less than 0.1 nmph, while decreasing costs.

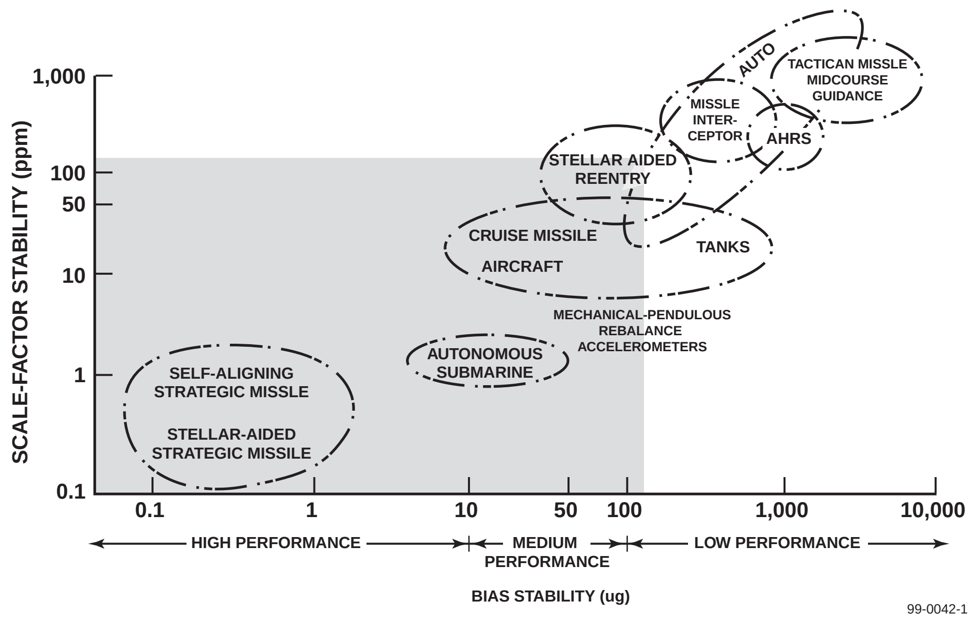

Figure 16.1-1. Accelerometer Technology Applications (shaded area is militarily critical region)

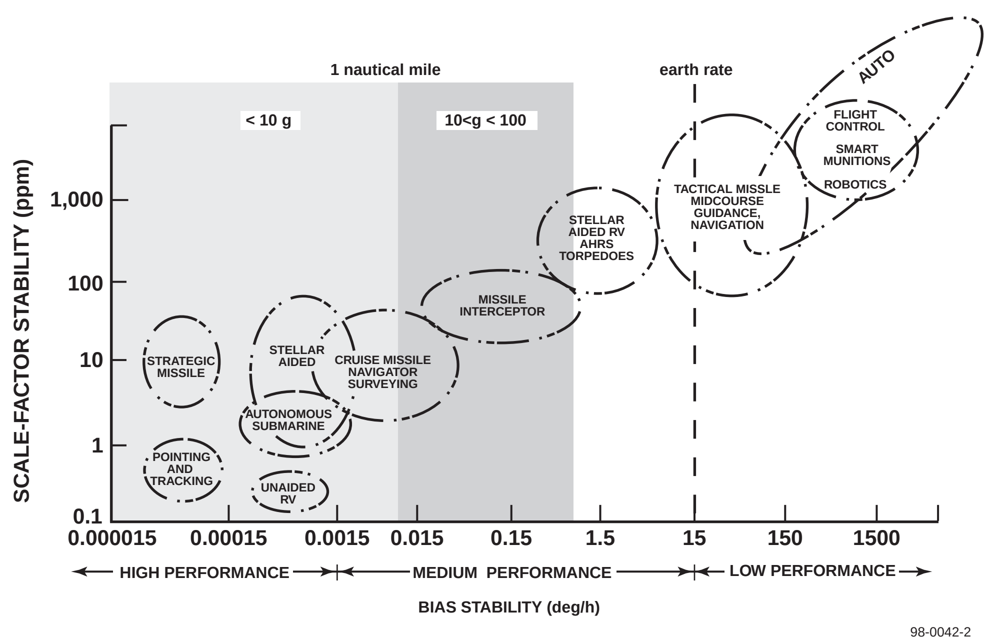

Figure 16.1-2. Gyroscope Technology Applications (shaded areas are militarily critical regions)

RATIONALE

INS technology (providing an autonomous, anti-jam, and covert capability of guidance and navigation) will continue to be critical for military use in the foreseeable future. The availability of the GNSS in a tightly coupled approach with the INS provides a system that is robust against jamming and satellite availability and more accurate than either INS or GNSS alone**.** However, the emergence of low cost INS, coupled with other sensors [forward-looking infrared radar (FLIR), LORAN, air data, gravimeters, radar and/or laser altimeter] and geo-referenced databases (digital terrain maps including magnetic and gravity data), will provide an alternative to GPS in a high jamming environment. Further improvements in hybrid INS systems, particularly DBRN, will increase covertness and accuracy without use of GNSS. This will lead to port-to-port submarine navigation capability without need to surface. These systems can also provide very accurate guidance and velocity data for an adversarial aircraft, missile, or WMD. The increased reliability and decreased cost of RLGs, FOGs, and MEMS gyros (gyro on a chip) will allow for an expanding list of military and commercial applications. An INS and its respective sensor components have wide applications in commercial transport and civil aircraft, surveying, research, and robotics. While this provides greater opportunities to develop these technologies rapidly, the transfer of technology for non-U.S. military advancements will be a challenge to prevent. Low cost, micromachined inertial technology is receiving wide commercial funding outside of the United States. The General Accounting Office (GAO)/National Security and International Affairs Division (NSIAD) Report 93-67 of March 1993 noted that "the technical data for nonmilitary INS is the same as for military INS and is particularly sensitive because it enables the licensee to manufacture all or part of the item." This quote is even more germane today.

Future key critical technologies are the emergence of low-cost, microminiaturized INS using MEMS (MEMS could revolutionize navigation). The commercial automotive markets are driving the MEMS technology development. Current MEMS gyroscopes are less than 5×1 cm, with an accuracy of 100 deg/hr at a cost of under $50. Industry expectations are to achieve 10 deg/hr by the end of 2000. Depending on military investments in that market, over the next 5–10 years MEMS-type gyroscopes could achieve tactical accuracy of 1.0 to 0.1 deg/hr.

Future miniaturization using NEMS sensors may be possible. The advantage would be the elimination of the gyroscope, using only accelerometers for sensing linear and rotational acceleration in a 360-deg cluster per axis. The issue is the sensitivity of the accelerometer to detect Earth's gravity because of the sensor's small mass and ability to detect quantum noise levels. Currently, the NEMS market driver is focused on medical commercial applications. This technology has been included because of its potential significant military benefits of reduced of INS cost and size. NEMS technology will lag MEMS technology by 10 years. Figure 16.1-3 shows the INS technology trends and costs projections over the next 10–20 years across multiple INS users. Figure 16.1-3 also shows that more sensor hybridization will occur over the next 5–10 years as GPS and other telecommunication functions are tightly coupled and integrated with INS. This massive production base, as well as the low cost of MEMS and NEMS sensors, could significantly reduce the cost of many military INS to less than $500. As the cost of INS decreases, their use in commercial applications will increase dramatically, especially in active robotic control. Current INS commercial applications already include stabilization of cameras (analogous to weapon sight stabilization) and automotive ride and stability control (analogous to turret stabilization). Foreign availability is increasing rapidly as the need for specialized manufacturing equipment and facilities decreases. Continued decreases in the cost and size of INS technology will affordably allow autonomous, non-jammable, and accurate INS to be installed on most DoD assets and even combat personnel, thereby providing a common coordinated reference system for the military battlespace.

The military dependency on GPS, with its inherent susceptibility in a jamming environment, has led to more use of INS tightly coupled with GPS in a hybrid INS configuration. The current tri-Service, embedded GPS/INS [embedded Global Positioning System inertial (EGI)] is an example of the movement of these separate systems (GPS and INS) into a single system, with the attendant reductions in size, weight, and cost.

Future technology advances in electronic miniaturization, such as GPS on a chip (refer to Subsection 16.3), as well as satellite-based telecommunication systems using trilateration timing signals (i.e., Celestri, Teledesic and 911 Cellular), will result in further combination of navigation and communications functions. A "seamless" navigation system using hybrid sensors is a must for urban warfare. The degree of coupling of these external and internal sources and the amount of filtering and state vectors in these filters all play a role in determining the accuracy of the resultant hybrid system. Hybrid navigation system technology is now a common topic at international navigation conferences, and the theory and practice of Kalman filters is well known throughout the world. It is possible to procure simulators from a wide range of commercial sources, and the algorithms are published in textbooks and journals. Use of multi-MEMS INS will provide greater accuracy, survivability, and fault tolerance for an autonomous military capability.

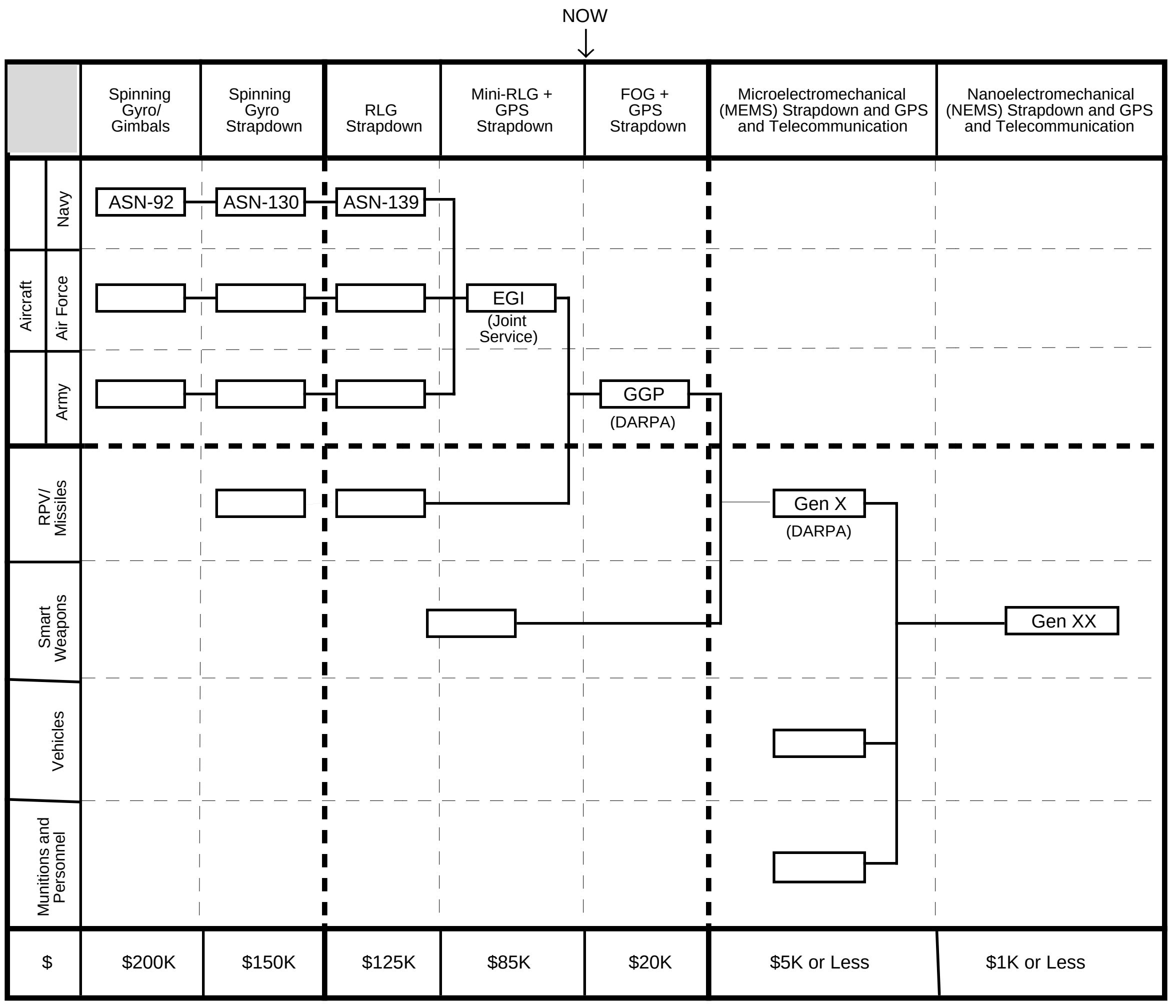

Figure 16.1-3. INS Technology Transition Trends[1]

Gyro astro-tracking devices could enhance navigation accuracy, where terrain and gravity data for geo-mapping may be difficult to obtain from certain areas and when GPS is unavailable. In addition, position errors increase for high altitude and space applications. An alternative approach to autonomous navigation utilizes an INS platform tightly coupled with a star tracker to bound the position error. Star-tracking-aided INS is particularly applicable to high-altitude and space applications. For example, a 1-nm/hr INS corrected by means of Kalman filtering with continuous star fix information can limit the position error on the order of 30 m. The tracker pointing errors, gravity compensation errors, and accelerometer instabilities are the dominant error sources. To achieve this position accuracy, tracker measurements and gravity and accelerometer compensations need to be accurate to approximately 1.0 arc sec each. These accuracies are available today at very high cost. Use of new technology trackers utilizing electro-formed optics on nickel bases with micro-precision sensor arrays, as well as improved processors, gravity

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[1] Excludes ship/submarine INS technology evolution because of its unique performance requirements.

compensations, and future generation strapdown inertial instruments, should significantly reduce cost, size, and weight.

WORLDWIDE TECHNOLOGY ASSESSMENT

The technology gap between the United States and other nations is rapidly closing. The United States leads the world in most inertial technology and is progressively improving in the areas of accuracy, alignment, size, weight, reliability, cost, and integration with digital processing technology. However, France, Israel, UK, China, Japan, and Russia are rapidly closing the gap. Russia and the China have produced conventional inertial products and have initial production capability in RLGs and FOGs. Russia has developed some flexure rotor and magnetically suspended gyroscopes, and the quality of these gyroscopes appears to be on a par with Western equipment. Because tuned-rotor gyroscopes are inexpensive and very suitable for a space reentry guidance application, the acquisition of this type of technology has enhanced gyroscopic capability in maneuvering UAVs. Nations developing an inertial capability include Australia, Brazil, China, India, Israel, Italy, Sweden, South Africa, and Norway. Their major obstacles are access to a market of sufficient size to justify the development costs and the capital equipment costs for high-volume production. The increasing use of inertial sensors in very high volume, nontraditional markets, such as automotive and smart shells, has the potential to tilt this paradigm dramatically.

Country	Inertial Navigation System (INS)	Hybrid Inertial Navigation Systems (including GNSS)	Gyro Astro Tracking Systems	Inertial Sensors
Australia	●●	●●	●●	●●
Austria	●	●		●
Brazil	●●	●		●
Canada	●●●	●●●●	●●●	●●●
China	●●●	●●●	●●●	●●●
Czech Republic	●	●		●
Finland	●	●		●
France	●●●●	●●●●	●●●●	●●●●
Germany	●●●●	●●●●	●●●●	●●●●
Hungary	●	●		●
India	●●●	●●●	●●	●●
Israel	●●●●	●●●	●●●	●●●
Italy	●●●●	●●●	●●	●●
Japan	●●●	●●●●	●●●	●●●
Netherlands	●●	●●●	●●●	●●
Poland	●	●		●
Romania	●	●		●
Russia	●●●●	●●●●	●●●●	●●●●
Slovak Republic	●	●		●
South Africa	●●●	●●●		●●●
South Korea	●●	●●		●●
Spain	●●	●●		●●
Sweden	●●	●●		●●
Switzerland	●●●	●●	●●●	●●
Taiwan	●●	●●		●●
UK	●●●●	●●●	●●●	●●●
Ukraine	●●●●	●●●●	●●●●	●●●
United States	●●●●	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.1-4. INS and Related Components WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-16.1. INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

DATA SHEET III-16.1. INERTIAL NAVIGATION SYSTEMS

Developing Critical Technology Parameter	In next 5 to 10 years: For aircraft, vehicle, or spacecraft for attitude, guidance, and control—navigation error < 0.2 nmi/hr 90% CEP. For ships—navigation error of < 1.0 nmi in 30 hrs. For missiles—navigation error of < 0.8 nmi/hr. Or specified to function at linear acceleration > 10 g on any platform. In addition, developing technology will be lighter and cheaper.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment. Ships motion simulator.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. INS alignment time for moving platform and transfer alignment techniques. Algorithms for gyro compensation, Kalman filter implementations, and sensor data processing.
Technical Issues	INS is the only self-contained, nonradiating, nonjammable, autonomous navigation technology. Alignment time versus accuracy. High latitude initialization problems. INS performance can be significantly improved by sequentially changing the gimbal orientation.
Major Commercial Applications	Aviation, ships, spacecraft.
Affordability	Miniaturization and larger volume markets will significantly reduce costs. Accuracy is a cost driver.

RATIONALE

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. These obstacles are being reduced or eliminated by more accurate gyroscope and accelerometer sensors, as well as advances in computer technology (memory and throughput), power quality, and electronics. Military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and C3 systems require high navigation accuracy capability. For submarines increased INS performance will result in increased covertness, thereby increasing mission effectiveness. Most current INS use optical gyroscopes: RLGs or FOGs. The move from the older, mechanical technologies has been driven by the commercial and military market demanding lower weight, lower power, and smaller size with improvements in reliability. Tuned rotor gyros, however, continue to be improved, and the size is decreasing. Land navigation that uses many of the older technologies is still viable, using hybridization with GPS. Over the next 5–10 years, RLG and FOG INS technology will continue to improve its free inertial performance from 1.0 nmph to less than 0.1 nmph, while decreasing costs. Future trends toward using MEMS sensors will continue to significantly decrease the cost of this technology.

Military applications of this technology will enhance the following:

- Vehicle, aircraft, spacecraft, ship, and submarine navigation
- Weather balloon navigation
- AUV navigation
- Air vehicle heading, attitude, and angle of attack
- Accurate velocity for weapon release/targeting
- Search and rescue
- Nuclear reset
- Situation awareness.

This technology supports the Joint Vision 2010 precision engagement by providing both delivery application and low-observable technology. This technology also supports the Joint Warfighting Science and Technology (S&T) Plan for precision force. The use of INS during GPS jamming and/or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets. In addition, this technology supports the Navy plan for a precise navigation system as a backup to GPS or as a successor system once the GPS technology becomes obsolete.

There are no special requirements (such as a cooperative agreement) for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Brazil	●●	Canada	●●●	China	●●●
France	●●●●	Germany	●●●●	India	●●●	Israel	●●●
Italy	●●●	Japan	●●●	Norway	●●●	Russia	●●●
Slovak Republic	●	South Africa	●●	South Korea	●●	Spain	●●
Sweden	●●	Switzerland	●●	Taiwan	●●●	UK	●●●
Ukraine	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The technology gap between the United States, Canada, and the UK and other nations is rapidly closing. The United States leads the world in most inertial technologies and is progressively improving in the areas of accuracy, alignment, size, weight, reliability, cost, and integration with digital processing technology. However, France, Israel, UK, Germany, China, Japan, and Russia are rapidly improving. Russia and the China have produced conventional inertial systems and have full production capability. Both countries have sponsored international symposia. Nations that are developing an inertial capability include Australia, Brazil, China, India, Israel, Italy, Sweden, South Africa, and Norway. Their major obstacles are access to a market of sufficient size to justify the development costs and the capital equipment costs for high-volume production.

The following organizations have active research programs:

- ***United States***
  - Astronautics (Kearfott)
  - Boeing
  - Crossbow Technologies
  - Draper Labs
  - Honeywell
  - Litton
  - Lockheed Martin
  - Northrop Grumman
  - Smith Industries
- ***Brazil***
  - Embraer
- ***Israel***
  - Elbit Systems
- ***Germany***
  - Daimler Chrysler Aerospace
  - LITEF
- ***France***
  - Aerospatiale Matra
  - Airbus Industries
  - SNECMA
- ***UK***
  - British Aerospace
  - Smith Industries
- ***Japan***
  - Mitsubishi Industries
- ***Italy***
  - Piaggio Aero Industries

DATA SHEET III-16.1. HYBRID INERTIAL NAVIGATION SYSTEMS (INCLUDING GNSS)

Developing Critical Technology Parameter	In next 5 to 10 years: For aircraft, vehicle, ship, missile or spacecraft—navigation error < 1 m 50% spherical error probable (SEP) in position, Or specified to function at linear acceleration > 10 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining INS with Doppler, GNSS, or DBRN. INS initial alignment software for moving platform, transfer align techniques, and reference to geoid.
Technical Issues	Use of Doppler, acoustic (bathymetric), stellar, gravity sensing, or terrain data from data bases to improve GNSS/INS beyond uncompensated control level. Except for Doppler and acoustic, these methods are self-contained, nonradiating, and nonjammable.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs.

RATIONALE

Hybrid INS/GNSS systems combine the best features of different navigation systems to provide an autonomous, covert, and nonjammable system that will locate our forces and, when used with other technologies, can locate enemy troops and targets. In surface and above-surface applications, the INS outputs can be optimally combined with GPS to produce a smooth, blended output, and if GPS is lost (or jammed), then the INS will produce a seamless navigation output. In this latter case increased INS performance will result in a more accurate navigation solution after loss of GPS. GPS by itself does not provide a north direction unless the sensor is moving. Therefore, a north reference from a gyrocompass, an INS, or a simple magnetic compass is needed. Using multiple GPS antennas, adequately spaced on a rigid body, will provide position information which can be used to derive an estimate of geographical heading. Future technology advances in electronic miniaturization, as well as satellite-based telecommunication systems using trilateration timing signals, will result in further combination of navigation and communications functions. "Seamless" navigation systems using hybrid sensors are a must for urban warfare. The degree of coupling of these external and internal sources and the amount of filtering and state vectors in these filters all play a role in determining the accuracy of the resultant hybrid system. Hybrid navigation system technology is now a common topic at international navigation conferences, and the theory and practice of Kalman filters, modern control theory, and other alternative estimation techniques are well known throughout the world. Simulators from a wide range of commercial sources are available, and the algorithms are published in textbooks and journals. Advanced alternative techniques to Kalman filters are routinely presented at international symposia and in the international academic community. There are little remaining effective control measures because of the widespread dissemination of this knowledge. Use of multi-MEMS INS will provide greater accuracy, survivability, and fault tolerance for an autonomous military capability.

This technology supports the Joint Vision 2010 precision engagement by providing both delivery application and low-observable technology. This technology also supports the Joint Warfighting Science and Technology (S&T) Plan for precision force. The use of INS during GPS jamming and/or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets. In addition, this technology supports the Navy plan for a precise navigation system as a backup to GPS or as a successor system once the GPS technology becomes obsolete.

Military applications of this technology will enhance the following:

- Supply location systems
- Spacecraft navigation
- Parachute insertion
- Air vehicle attitude and angle of attack
- Battlefield targeting
- Helicopter hover positioning
- Gravity measuring system
- HF communications frequency management
- Encryption/decryption
- DGPS
- Ship cargo management
- Situation awareness
- Minefield positioning
- Search and rescue
- Weather balloon navigation
- Inertial navigator reset and mapping
- System integration of sensors
- Pseudolite positioning system
- Position reporting for high-value assets
- AUV navigation
- Artillery smart round
- Differential GPS for heading
- Nuclear reset
- Construction

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Brazil	●	Canada	●●●	China	●●●
France	●●●●	Germany	●●●●	India	●●●	Israel	●●●
Italy	●●●	Japan	●●●	Norway	●●	Russia	●●●
South Africa	●●●	South Korea	●●	Spain	●●	Sweden	●●
Switzerland	●●	Taiwan	●●	UK	●●●	Ukraine	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Hybrid INS technology is being carried out throughout the industrialized world. At the present time, the United States, France, and Germany appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - Astronautics
  - Crossbow Technologies
  - Honeywell
  - Lockheed Martin
  - Smith Industries
  - Boeing
  - Galaxy Scientific Corporation
  - Litton
  - Northrop Grumman

- ***Brazil***
  - Embraer
- ***Israel***
  - Elbit Systems
- ***Germany***
  - Daimler Chrysler Aerospace
  - LITEF
- ***France***
  - Aerospatiale Matra
  - Airbus Industries
  - SNECMA
- ***UK***
  - British Aerospace
  - Smith Industries
- ***Japan***
  - Mitsubishi Industries
- ***Italy***
  - Liral
  - Piaggio Aero Industries

DATA SHEET III-16.1. GYRO ASTRO-TRACKING INERTIAL NAVIGATION SYSTEMS

Developing Critical Technology Parameter	In next 5 to 10 years: Navigation error < 0.1 nmph 50% CEP; Azimuth accuracy < 50 arc seconds; Or specified to function at linear acceleration > 10 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters.
Technical Issues	Alignment or start-up time versus accuracy. Large size, high weight, and high cost restrict applications to high valued platforms.
Major Commercial Applications	Spacecraft stabilization and basic geodetic research.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

RATIONALE

Gyro astro-tracking systems improvements are critical to improving covert accuracy and reducing cost. The military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, and surface ships. Targeting, surveillance, and C3 systems require high navigation accuracy. Many current astro trackers use optical gyroscopes such as the RLG. RLG and INS technology will continue to improve gyro astro tracker performance while decreasing costs. Future trends toward using MEMS sensors, advanced optics, and infrared sensors will continue to decrease the cost and increase the application of this technology.

Joint Vision 2010 identifies this technology because it supports precision engagement by providing both delivery application and low-observable (covert) technology. The Joint Warfighting S&T Plan also supports this technology for precision force. Its use during GPS jamming or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Brazil	●	Canada	●●	China	●●
Denmark	●●●	France	●●	Germany	●●●	India	●●
Israel	●●	Italy	●●	Japan	●●	Netherlands	●
Russia	●●●	Switzerland	●●	UK	●●	Ukraine	●
United States	●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A space-based stellar compass has been developed at the Technical University of Denmark. This stellar compass with a low mass, low power consumption, and fully autonomous operation, providing a high accuracy quaternion output and low-cost implementation, represents an advance in the art of star trackers. The stellar compass shows promise for both government and commercial use if both cost and weight can be significantly reduced. Obtaining space-qualified hardware that will be needed for future warfighting requirements is one of the objectives of the Navy's Space S&T Council.[2]

Russia and China have produced conventional astro trackers. Their major obstacles are access to a market of sufficient size to justify the development costs and the capital equipment costs for high-volume production.

Gyro astro tracking inertial navigation technology is limited because of its costs and limited commercial applications. At the present time the United States, Russia, Denmark, and Germany appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - Astronautics (Kearfott)
  - Litton
  - Northrop-Grumman
  - U.S. Naval Observatory
- ***Denmark***
  - University of Denmark
- ***Russia***
  - Astro-IKI
  - Kuznetsov Research Institute for Applied Mechanics

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[2] *Space Newsletter No 2: Örsted Stellar Compass,* Office of Naval Research Newsletter, European Office.

DATA SHEET III-16.1. RING LASER GYROSCOPES (RLG)

Developing Critical Technology Parameter	In next 5 to 10 years: Drift rate stability of < 0.005 deg/hr for < 10 g, or Drift rate stability of < 25 deg/hr for 10 to 100 g, or Specified to function at linear acceleration levels > 100 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Technical Issues	Alignment time versus accuracy. High costs for initial national capability. Dynamic range up to 400 deg/sec. Lock-in problem at very low turn rates. Requires compensation capability or alternative designs. Surface finish of mirror is a major error source.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

RATIONALE

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. RLG inertial sensor improvements are critical to improving accuracy and reducing cost. The military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and C3 systems require high navigation accuracy. Many current INS use optical gyroscopes such as the RLGs. Over the next 5–10 years, RLG technology will continue to improve free inertial sensor performance from 1.0 nmph to less than 0.1 nmph, while decreasing costs. Applications include single-axis and multi-axis (cube) sensors.

Joint Vision 2010 supports this technology for precision engagement by providing both delivery application and low observable technology. The Joint Warfighting S&T Plan also supports this technology for precision force. Its use during GPS jamming or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●●●	China	●●●	France	●●●
Germany	●●●	India	●	Israel	●●	Italy	●●
Japan	●●●	Netherlands	●●	Russia	●●●	South Africa	●●
South Korea	●●	Taiwan	●●	UK	●●●	Ukraine	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The technology gap between the United States and other nations is rapidly closing. The United States leads the world in most inertial technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration of RLG inertial sensors. However, France, Israel, UK, China, Japan, and Russia are rapidly closing the gap. Russia and China have produced conventional inertial systems and have initial production capability in RLG. Nations that are developing an inertial sensor capability include Australia, Brazil, China, Japan, India, Israel, Italy, Sweden, South Africa, and Norway. Their major obstacles are access to a market of sufficient size to justify the development costs and the capital equipment costs for high-volume production. The increasing use of inertial sensors in very high volume, nontraditional markets, such as automotive and smart shells, has the potential to tilt this paradigm dramatically.

The following organizations have active research programs in RLG technology:

- ***United States***
  - Astronautics (Kearfott)
  - Boeing
  - Honeywell
  - Litton
  - Lockheed Martin
  - Northrop-Grumman
  - Smith Industries
- ***Brazil***
  - Embraer
- ***Israel***
  - Elbit Systems
- ***Germany***
  - Daimler Chrysler Aerospace
  - LITEF
- ***France***
  - Aerospatiale Matra
  - Airbus Industries
  - SFIM
- ***UK***
  - British Aerospace
  - Smith Industries
- ***Japan***
  - Hitachi
  - Mitsubishi Industries

DATA SHEET III-16.1. FIBER-OPTIC GYROSCOPES (FOG)

Developing Critical Technology Parameter	In next 5 to10 years: Drift rate stability of < 0.01 deg/hr for < 10 g, or Drift rate stability of < 0.25 deg/hr for 10 to 100 g, or Specified to function at acceleration levels > 100 g on any platform. In addition, developing technology will be lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Technical Issues	Reduce environmental sensitivities. Reduce or eliminate dead band at zero input rates. Alignment time versus accuracy. Reliance on commercial optical fiber industry for high-quality fiber. Fiber-winding technology. Optimum sensor for low-cost hybridization with other sensors such as GPS integrated optics.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

RATIONALE

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. FOG inertial sensor improvements are critical to improving accuracy and reducing cost. The military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and C3 systems require high navigation accuracy. Most current INS use RLGs. INS with FOG are significantly lower in cost than RLGs, and are just now being introduced in military applications requiring less accuracy than RLGs. In the next 5–10 years, however, FOG INS technology will continue to improve INS performance from 2.0 nmph to less than 0.4 nmph, while decreasing costs. Further accuracy improvement requires a better gravity model for INS with FOG sensors.

The Joint Vision 2010 supports this technology for precision engagement by providing accurate delivery application. The Joint Warfighting S&T Plan also supports this technology for precision force. Inertial sensor use during GPS jamming or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets. The Navy plan identifies miniature navigation systems as a key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Brazil	●	Canada	●	China	●●
France	●●●	Germany	●●●	Israel	●	Japan	●●●
Netherlands	●●	Russia	●●●	South Africa	●	South Korea	●
Sweden	●	Switzerland	●	Taiwan	●	UK	●
Ukraine	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The technology gap between the United States and other nations is rapidly closing. The United States leads the world in most inertial technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration of FOG inertial sensors. However, France, Israel, UK, China, Japan, and Russia are rapidly closing the gap. Russia and China have produced conventional inertial systems and have initial production capability in FOG. Nations that are developing an inertial sensor capability include Australia, Brazil, China, India, Israel, Italy, Sweden, South Africa, and Norway. Their major obstacles are access to a market of sufficient size to justify the development costs and the capital equipment costs for high-volume production. The increasing use of inertial FOG inertial sensors in very high volume, nontraditional markets, such as automotive and smart shells, has the potential to tilt this paradigm dramatically.

The following organizations have active research programs:

- ***United States***
  - Astronautics (Kearfott)
  - Boeing
  - Crossbow
  - Fibersense Technology Corp.
  - Honeywell
  - KVH Industries
  - Litton
  - Lockheed Martin
  - Northrop-Grumman
  - Smith Industries
- ***Israel***
  - Elbit Systems
- ***Germany***
  - Deutschland GmbH
  - LITEF
- ***France***
  - Aerospatiale Matra
  - Airbus Industries
  - SFIM Industries and Photonetics (consortium)
- ***UK***
  - British Aerospace
  - Smith Industries
- ***Japan***
  - Hitachi
  - Mitsubishi Industries
- ***China***
  - Kwangwoon University

DATA SHEET III-16.1. MICROELETROMECHANICAL SYSTEMS (MEMS) GYROSCOPES AND ACCELEROMETERS

Developing Critical Technology Parameter	In next 5 to 10 years: Gyroscope: Drift rate stability of < 0.05 deg/hr for < 10 g, or Drift rate stability of < 0.5 deg/hr for 10 to 100 g, or Specified to function at linear acceleration levels > 100 g on any platform. Accelerometer: Bias stability of 400 µg, or Scale factor stability of 300 ppm.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed manufacturing test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Technical Issues	With respect to frequency stability, as the dimensions get smaller, the noise gets worse. Orthogonality of sensors requires compensation due to miniaturization (mechanical limits). Inherently capable of operation in extreme high g environment (artillery). Quantum noise and frequency measurement.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization will increase application of this technology. Larger volume markets will significantly reduce costs.

RATIONALE

An INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Improvements of MEMS gyroscopes and accelerometers are critical to improving accuracy and reducing cost. The combination of size, weight, power, and cost requirements are driving the development of MEMS technology. Military applications in the next 5 to 10 years include both strategic and tactical systems: missiles, UAVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and C3 systems require high navigation accuracy. Most current INS use optical gyroscopes such as RLGs or FOGs. MEMS gyroscope and accelerometer technology could continue to improve free inertial sensor performance over the next 5–10 years from 10 nmph to less than 3.0 nmph, while decreasing costs, if quantum noise and frequency measurement issues are resolved. Future trends toward using NEMS sensors will continue to decrease the cost of these sensors. Applications include single-axis and multi-axis (cube) sensors.

Joint Vision 2010 supports this technology for precision engagement by providing accurate delivery application more affordably. The Joint Warfighting S&T Plan also supports this for precision force. MEMS sensor use during GPS jamming or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets. The Navy plan identifies miniature navigation systems as key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

Point Research Corporation, a U.S. company, has developed a dead-reckoning system for the Land Warrior using a triad of magneto-resistive magnetometers for heading determination and a triad of MEMS accelerometers for tilt compensation of the magnetometers and footstep detection. Because of its size and cost reductions over current INS, the system also could be used as a terminal guidance system for smart munitions (i.e., mortars and artillery shells).

Continued research is needed to resolve the issue of noise measurement. The following key development areas should be pursued.

- Develop resonators of temperature-compensated materials
- Measure quantum noise vs. frequency to determine scaling laws
- Measure nonlinear effects (drive level sensitivity, acceleration sensitivity, and thermal transient effect)
- Measure noise vs. helium and hydrocarbon pressures (to measure effects on temperature fluctuation noise, Johnson noise, and adsorption-desorption noise).

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●●	France	●●●	Germany	●●●
India	●	Israel	●●	Italy	●	Japan	●●●
Netherlands	●●	Norway	●	Russia	●●	South Africa	●
South Korea	●●	Spain	●●	Sweden	●●	Switzerland	●●
Taiwan	●●	UK	●●●	Ukraine	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States leads the world in MEMS technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration of this technology. However, France, Germany, UK, and Japan are rapidly closing the gap. The paradigm that high development and production cost of new technology in itself limits accessibility has the potential of dramatically changing because of MEMS technology's significantly lower production costs. MEMS technology has the greatest potential of opening this INS capability to nontraditional markets and nations. This field is receiving extensive support from the commercial and automotive industries.

The following organizations have active research programs:

- ***United States***
  - Advanced Micro Machines, Inc.
  - Analog Devices Incorporated
  - Astronautics (Kearfott)
  - Crossbow Technologies
  - DARPA
  - Draper Labs
  - Honeywell
  - IntelliSense Corporation
  - Litton
- ***Denmark***
  - Mikroelecktronik Centret
  - Technical University of Denmark

- ***Germany***
  - Fraunhofer Institute
  - HSG-IMIT
  - LITEF GmbH
- ***UK***
  - Encoder Technology
  - Surface Technology Systems
- ***Spain***
  - Centro Nacimal de Microelectronica
- ***Sweden***
  - Volvo Car Corporation
- ***Japan***
  - Hitachi
  - Nippondenso
  - Nissan
- ***France***
  - CEA-LETI
  - SAGEM
  - Sextant Avionique
  - SGS-Thompson
  - TIMA
  - University of Bordeaux

DATA SHEET III-16.1. ACCELEROMETERS OTHER THAN MICRO-MACHINED DEVICES

Developing Critical Technology Parameter	In next 5 to 10 years: Bias stability of < 100 µg, or Scale factor stability of < 80 ppm, or Specified to function at linear acceleration levels > 100 g on any platform. In addition, developing technology will be lighter and less expensive by factor of 10.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment; accelerometer axis align stations; ion milling; Plaza Arc; electronic sputtering.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Technical Issues	Orthogonality of sensors requires compensation due to miniaturization. Inherently capable of operation in extreme high g environment (artillery).
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

RATIONALE

This technology is a major component of an INS that is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Improvements in accelerometers other than micro-machined devices are critical to improve accuracy and reduce cost. The military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and C3 systems require high navigation accuracy. Future trends toward using MEMS sensors will continue to decrease the cost of this technology.

Joint Vision 2010 supports this technology for precision engagement by providing both accurate delivery application and low-observable technology. The Joint Warfighting S&T Plan also supports this technology for precision force. Its use during GPS jamming or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets. The S&T plan also identifies miniature navigation systems as key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Brazil	●	Canada	●●	China	●●●
France	●●●	Germany	●●●	India	●●	Israel	●●●
Italy	●●	Japan	●●●	Norway	●●	Russia	●●
Slovak Republic	●	South Africa	●●	Sweden	●●	Switzerland	●
UK	●●●	Ukraine	●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States leads the world in this technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration of inertial sensors. However, France, Germany, Israel, UK, China, and Japan are rapidly closing the gap. Nations that are developing this inertial sensor capability include Australia, Brazil, India, Italy, Sweden, South Africa, Russia, and Norway. Their major obstacles are access to a market of sufficient size to justify the development costs and the capital equipment costs for high-volume production. The use of accelerometers other than micro-machined devices in very high volume, nontraditional markets, such as automotive and smart shells, has the potential to tilt this paradigm dramatically. However, it appears that the automotive and munitions market will bypass improvements in this area and drive the technology to MEMS and NEMS.

The following organizations have active research programs:

- ***United States***
  - Honeywell
  - Litton
- ***UK***
  - Encoder Technology

DATA SHEET III-16.1. NANOELECTROMECHANICAL SYSTEMS (NEMS) ACCELEROMETERS

Developing Critical Technology Parameter	In next 10 to 20 years: Bias stability of < 200 µg, or Scale factor stability of < 200 ppm, or Specified to function at linear acceleration levels > 100 g on any platform. In addition, developing technology will be lighter and less expensive by factor of 10.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment; accelerometer axis align stations.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters Error compensation for environmental effects and technology characteristics
Technical Issues	Size reduction limited by proof mass of sensor. With respect to frequency stability, as the dimensions get smaller, the noise gets worse. Orthogonality of sensors requires compensation due to miniaturization. Inherently capable of operation in extreme high g environment (artillery). Quantum noise and frequency measurement.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

RATIONALE

This technology has the potential of providing a significant reduction in the cost of an INS. INS is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs This technology is currently in its embryonic stage, with limited R&D investments. Over the next 10–20 years, however, development of NEMS accelerometers has the greatest potential to bring INS technology to the widest military applications, providing autonomous navigation at significantly reduced cost. The military applications are the same as those for current INS: strategic and tactical systems—missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Additional usages may be possible because of NEMS' significantly lower cost for increased battlefield situational awareness, small munitions, artillery shells, mortars, and miniature AUVs.

Joint Vision 2010 supports this technology for precision engagement, by providing both accurate delivery application and low-observable technology more affordably. The Joint Warfighting S&T Plan also supports this technology for precision force. Its use during GPS jamming or loss and its all-weather capability will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets. The S&T plan identifies miniature navigation systems as key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

Continued research needs to resolve the issue of quantum noise issues. The following key development areas should be pursued.

- Develop resonators of temperature-compensated materials
- Measure quantum noise vs. frequency to determine scaling laws
- Measure nonlinear effects (drive level sensitivity, acceleration sensitivity, and thermal transient effect)
- Measure noise vs. helium and hydrocarbon pressures (to measure effects on temperature fluctuation noise, Johnson noise, and adsorption-desorption noise).

WORLDWIDE TECHNOLOGY ASSESSMENT

Denmark	●	Germany	●	Japan	●	UK	●
United States	●						

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

This technology is in its embryonic stage, with very few nations currently investing in it for applications in INS. This is seen as an evolutionary path for MEMS.

The following organizations have active research programs in nanotechnology:

- ***Denmark***
  - Mikroelecktronik Centret
  - Technical University of Denmark
- ***United States***
  - Cornell University
  - Draper Labs
  - Rice University
- ***UK***
  - Oxford University
- ***Japan***
  - National Institute for Advanced Interdisciplinary Research

SECTION 16.2—GRAVITY METERS AND GRAVITY GRADIOMETERS

Highlights

- Gravity sensor arrays will be more viable due to accurate time sequencing, computer speed, and memory advances, providing increased detection and location of submarines, mines, and mobile missiles.
- Uncompensated gravity disturbances are a large error source for INS initialization and subsequent field operation. Future gravity models will enable more accurate INS compensation.
- Use of a worldwide gravity database based on better instrumentation and storage/access capabilities, in conjunction with on-board gravity sensors, will provide autonomous and continuous updates to INS, yielding comparable accuracy with projected INS/GPS hybrid systems.
- A developing technology to compute real-time gravity data from a moving platform may use the difference in acceleration data from an uncompensated INS and the GNSS.

OVERVIEW

This evolving and developing technology is used to measure a body's gravity field (such as Earth's), which in turn has applications for detection and localization of mass distributions, covert position determination, and inertial navigation compensation. Increasingly, gravity data will play a major and critical role in future navigation systems. Accurate geodetic and geophysical data (G&G) can improve the performance of inertial navigation systems to what may be near-GPS accuracy. G&G-enhanced INS could prove to be a significant navigation asset when GPS is not available. Specifically, future uses of G&G data will improve military weapon accuracy and increase safety of military and civilian flight by:

- Improving accuracy of navigation subsystems and stand-alone INS
- Providing accurate navigation in a hostile environment when GPS is denied
- Enabling covert terrain-following and terrain-avoidance systems
- Providing accurate attitude control of AUVs to allow for geodetic quality imagery
- Detecting underground manmade and natural structures and mass differences.

Present aircraft and ship INS use coarse models of Earth's gravity to correct for the sensed acceleration of gravity by the system sensors. Gravity anomalies that are not modeled are a major error source and limit the dynamic performance of deployed INS. Gravity meters and gravity gradiometers are used in static or mobile modes to measure gravity disturbances, deflections of the vertical, and to characterize the three-dimensional gravity vector.

G&G data is used to ground align and provide real-time, in-flight updates of local gravity to navigation systems, and these data are critical to both future precision engagement and safety of navigation requirements. Commercially, gravity meters and gradiometers are used to assist in exploration for oil, gas, or minerals by measuring the variations in the magnitude of the gravity vector or the variation in the gravity gradients. Furthermore, G&G data can be assimilated into "gravity maps" in support of data-based, POSITIME-referenced navigation systems (see Section 16.3).

Other uses include tunnel detection, buried material detection, and in arms control regimes, cargo identification, and weigh-in-motion. Covert detection and intrusion classification capabilities are militarily significant, especially for monitoring "secure" urban areas. International cooperative efforts through the International Association of Geodesy (IAG) exist for comparing absolute gravity standards.

RATIONALE

Moving-base gravity-meter accuracy is essential to generate maps for autonomous siting, INS initialization, and en-route compensation for in-flight gravity effects for WMD delivery systems, such as ballistic missiles and other long-range, unaided, inertial-guided applications including aircraft, AUVs, cruise missiles, and submarines. Applications have been developed to correct, either indirectly or directly, for the local gravity disturbances or vertical deflection on a moving base/platform. The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity-meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. In the latter mode, the spatial gravity gradients are multiplied (scalar product) by the velocity vector and integrated to obtain the vertical deflection in real time.

Another application for this technology is to use the gravity meter or gravity gradiometer in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, these accuracies could only be obtained at low altitude, if at all. Navigation at GPS accuracy through turns and acceleration is questionable, but could potentially be recovered afterward. These map-matching techniques using sensors giving data only along the flight path are questionable for long-term navigation, as there are likely to be areas where the data does not have adequate spatial variance to achieve these accuracies. In a local area, with proper conditions for the sensor type being used, these POSITIME methods might be useful. Gravity gradiometers have a higher military value than gravity meters, since they have the ability to estimate vertical deflection in real time; however, gravity meters for airborne and marine applications are still of military importance. Gravity meters and gravity gradiometers require stabilization and the associated software to maintain a stable reference frame. The resulting hybrid system has the potential to provide the military with a non-emanating, nonjammable, totally covert system that can be used worldwide for navigation. As noted, the system will require previously surveyed gravity map data as well as a sufficiently distinct gravity signature that can be detected in the background noise. When there is not an adequate signature, the system maybe augmented with magnetic signature map matching (see Section 16.4). Another developing method of determining gravity is by computing the acceleration difference between an uncompensated INS and a GNSS. As measured by a GNSS, the computed acceleration of the platform is the pure acceleration of the vehicle, while the acceleration measured by an uncompensated INS contains the gravity vector and the platform acceleration vector. The difference is the gravity vector. Advanced filtering using optical correlators/processors and GNSS time synchronization are enabling technologies to obtain the gravity vector.

WORLDWIDE TECHNOLOGY ASSESSMENT

State of the art in mass-produced gravity meters (gravimeters) is at the 5- to 10-µgal level. A specially configured LaCoste Romberg unit has yielded gravity measurements at precision and accuracy levels of 1-µgal. A few countries have elected to be dominant in gravity meter and gravity gradiometer technologies, while others are not active in the technology because of economic considerations. Gravity meters (static mode) better than 10 µgals are manufactured and used in the United States. Canada, Germany, UK, Japan, China, Russia, and the Ukraine have developed gravity meters that have not yet achieved the 10-µgal level. In moving base instruments, several state-of-the-art gravity meters are currently being manufactured to yield mgal-level precision in the United States and Germany. All require the use of very high-grade accelerometers and are considered to be of high enough quality to be of military importance because the accelerometers are of higher grade than those found in most INS. State of the art in gravity gradiometers is on the order of Eotvos/√Hz. This sensitivity is realized in Lockheed Martin (formerly Bell) systems, which are the only mobile systems currently available. Researchers at Yale University are developing an atom interferometry-based gradiometer with a sensitivity potential of 1 Eotvos/√Hz using a 1-m baseline. A team in New Zealand is developing a cryogenic gradiometer with potential sensitivity of 0.02 Eotvos/√Hz.

Countries of concern may not use (or develop) gravity technologies because of their technical complexity, high cost, and marginal military benefits. The alternative of using data from INS and GPS (or other aids) may prove to be more cost effective as a developing technology for data base generation. Countries with proven capability to use this technology for ballistic missiles include the United States, UK, Russia, Ukraine, China, France, and Canada.

Country	Gravity Meters (Gravimeters) Absolute	Gravity Meters (Gravimeters) Relative	Gravity Gradiometers
Australia	●●	●●●	●●●●
Austria	●●	●●●●	
Brazil	●●	●●●●	
Canada	●●●	●●●●	●●
China	●●●	●●●●	●●●●
Czech Republic	●●●	●●●●	
Finland	●●●	●●●●	●●
France	●●●	●●●●	●●●●
Germany	●●●	●●●●	●●
Hungary	●●	●●●●	●●
India	●●	●●●	●
Israel	●●	●	●●
Italy	●●●●	●●●●	●●●●
Japan	●●●●	●●●●	●●
Netherlands	●●	●●	
Poland	●●	●●●	
Romania	●●	●●●	
Russia	●●●●	●●●●	●●●●
Slovak Republic	●●	●●●	
South Africa	●	●●	
South Korea	●	●	
Spain	●	●●	
Sweden	●●	●●●●	
Switzerland	●●	●●●●	
Taiwan	●	●●	
UK	●●●	●●●●	●●●●
Ukraine	●●	●●●●	●●●
United States	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.2-1. Gravity Meters and Gradiometers WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-16.2. GRAVITY METERS AND GRAVITY GRADIOMETERS

DATA SHEET III-16.2. GRAVITY METERS (GRAVIMETERS), NONMOBILE USE

Developing Critical Technology Parameter	In next 5 to 10 years: Accuracy of < 50 µgals with a time-to-steady-state registration of less than 2 minutes under any combination of attendant corrective compensation. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	SQUID sensors require superconducting temperature Dewars.
Unique Software	Algorithms and verified data for real-time gravity compensation and detection (improvement > 10 to 1) for operation using arrays.
Technical Issues	Accurate verticality and low-level vibration environment required.
Major Commercial Applications	Resource exploration. Detection of underground structures.
Affordability	Cost is proportional to usage. This is not a large-volume production technology. One of the largest manufacturers has sold only about 1,500 units in the last 40 years.

RATIONALE

Gravity meters are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for verticality for sensor stabilization.

The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect, and most common, compensation technique uses vertical deflection map data computed from gravity meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. Another application for this technology is to use the gravity meter in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, this accuracy could only be obtained at ground level or low altitude, if then. In a local area, with proper conditions for the sensor type being used, these methods might be useful.

The knowledge of initial conditions of gravity predetermines accuracy of self-contained, autonomous navigation systems of all types, but especially inertially equipped ballistic missiles. The knowledge of the gravity field allows accurate compensation of INS. Gravity databases are required for strategic aircraft, submarines, unmanned vehicles, and missiles. The detection of underground structures and material composition are other applications. Continuing development of gravity meter arrays using advanced correlation techniques and very accurate clocks will improve the signal-to-noise ratio (SNR) of the array system. This is considered to be a militarily critical capability.

Advanced filtering using optical correlators/processors and GNSS time synchronization are enabling technologies to obtain the gravity vector. Once the gravity map is generated, nonmobile gravity meters can be used for correlation of the grid data.

Relative to JCS Vision 2010, gravity meters have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●●●	Brazil	●●●	Canada	●●●
China	●●●●	Czech Republic	●●●	Finland	●●●●	France	●●●●
Germany	●●●●	Hungary	●●●	India	●●	Israel	●●
Italy	●●●●	Japan	●●●●	Netherlands	●●	Poland	●●●
Romania	●●	Russia	●●●●	Slovak Republic	●●●	South Africa	●
South Korea	●	Spain	●●	Sweden	●●●	Switzerland	●●●
Taiwan	●	UK	●●●	Ukraine	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. State of the art in mass-produced gravity meters (gravimeters) is at the 5- to 10-µgal level. A specially configured LaCoste Romberg unit has yielded gravity measurements at precision and accuracy levels of 1 µgal. A few countries have elected to be dominant in gravity meter technologies, while others are inactive in this area because of economic considerations. Gravity meters (static mode) better than 10 µgals are manufactured and used in the United States. Canada, Germany, UK, Japan, China, Russia, and the Ukraine have developed gravity meters that have not achieved the 10-µgal level.

Countries of concern may not use (or develop) gravity meters because of their technical complexity, high cost, and marginal military benefits. The alternative of using data from INS and GPS (or other aids) may prove to be more cost effective as a developing technology for data-base generation. Countries with proven capability to use this technology for ballistic missiles include United States, UK, Russia, Ukraine, China, France, and Canada.

The following organizations have active research programs:

- ***United States***
  - Carson Instruments
  - Exploration Instruments
  - Gravity Exploration Techniques, Inc.
  - Gravity Map Services
  - GWR Instruments
  - LaCoste Romberg
  - Neese Instrument Company
  - Scinrex
  - Worden Meter Company
  - ZLS Corporation
  - µG

DATA SHEET III-16.2. GRAVITY METERS (GRAVIMETERS), MOBILE USE

Developing Critical Technology Parameter	In next 5 to 10 years: Moving platform accuracy of < 75 µgals with a time-to-steady-state registration of less than 2 minutes under any combination of attendant corrective compensation. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment to obtain mobile accuracy. Accelerometer axis align stations.
Unique Software	Algorithms and verified data for real-time gravity compensation and detection (improvement > 10 to 1) for operation on mobile platforms or using arrays and time compensation, or both.
Technical Issues	All modern earthbound gravity meters are affected by motion from all sources (seismic, acoustic, temperature, etc.) and require isolation/compensation. The problem is compounded by mobile usage by the need for compensation.
Major Commercial Applications	Resource exploration. Underwater terrain estimation. Detection of underground structures.
Affordability	Cost is proportional to usage. This is not a large-volume production technology.

RATIONALE

Gravity meters on a moving platform are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for velocity and verticality compensation for sensor stabilization.

Moving-base gravity-meter accuracy is essential to generate maps for autonomous siting, INS initialization, and en-route compensation for in-flight gravity effects for WMD delivery systems, such as ballistic missiles and other long-range, unaided, inertial-guided applications, including aircraft, AUVs, cruise missiles, and submarines. Applications have been developed to correct, either directly or indirectly, for the local gravity disturbances or vertical deflection on a moving base/platform. The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. In the latter mode, the spatial gravity gradients are multiplied (scalar product) by the velocity vector and integrated to obtain the vertical deflection in real time.

Another application for this technology is to use the gravity meter in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, this accuracy could only be obtained at low altitude, if at all. Navigation at GPS accuracy through turns and acceleration is questionable, but could potentially be recovered afterward. These map-matching techniques using sensors giving data only along the flight path are questionable for long-term navigation, as there are likely to be areas where the data does not have adequate spatial variance to achieve this accuracy. In a local area, with proper conditions for the sensor type being used, these methods might be useful.

The knowledge of initial conditions of gravity predetermines the accuracy of self-contained, autonomous navigation systems of all types, but especially those for ballistic missiles. The knowledge of the gravity field allows accurate compensation of INS. On mobile platforms, continuing development of gravity meter arrays using advanced correlation techniques and very accurate clocks will improve the SNR of the array system. Accurate time is required for compensation. This is considered to be a militarily critical capability.

Gravity meters for airborne and marine applications are of military importance. Gravity meters require stabilization and the associated software to maintain a stable reference frame. The resulting hybrid system has the potential to provide the military with a non-emanating, nonjammable, totally covert system that can be used worldwide for navigation. As noted, the system will require previously surveyed gravity map data as well as a unique gravity signature, which can be detected in the background noise. When there is not an adequate signature, the system may be augmented with magnetic signature map matching (see Section 16.4).

Another developing method of determining gravity is by computing the acceleration difference between an uncompensated INS and a GNSS. The computed acceleration of the platform, as measured by a GNSS, is the pure acceleration of the vehicle, while the acceleration measured by an uncompensated INS contains the gravity vector and the platform acceleration vector. The difference is the gravity vector. Advanced filtering using optical correlators/processors and GNSS time synchronization are enabling technologies to obtain the gravity vector.

Relative to JCS Vision 2010, gravity meters have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●●●	Brazil	●●	Canada	●●●●
China	●●●●	Czech Republic	●●●	Finland	●●●	France	●●●●
Germany	●●●●	Hungary	●●	India	●●●●	Israel	●●
Italy	●●●	Japan	●●●●	Netherlands	●●	Poland	●●●
Romania	●●	Russia	●●●●	Slovak Republic	●●●	South Africa	●●
South Korea	●	Spain	●●	Sweden	●●●	Switzerland	●●●
Taiwan	●●●	UK	●●●●	Ukraine	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. State of the art in mass-produced gravity meters (gravimeters) is at the 5- to 10-µgal level. A specially configured LaCoste Romberg unit has yielded gravity measurements at precision and accuracy levels of 1 µgal. A few countries have elected to be dominant in gravity-meter technologies, while others are passive because of economic considerations. In moving-base instruments, several state-of-the-art gravity meters are currently being manufactured to yield mgal-level precision in the United States and Germany. All require the use of very high-grade accelerometers and are considered to be of high enough quality to be of military importance because the accelerometers are of higher grade than those found in most INS.

Countries of concern may not use (or develop) gravity meters because of their technical complexity, high cost, and marginal military benefits. The alternative of using data from INS and GPS (or other aids) may prove to be more cost effective as a developing technology for data-base generation. Countries with proven capability to use this technology for ballistic missiles include the United States, the UK, Russia, Ukraine, China, France, and Canada.

The following organizations have active research programs:

- ***United States***
  - Exploration Instruments
  - LaCoste Romberg
  - Worden Meter Company (Texas Instruments)
  - GWR Instruments
  - Neese Instrument Company
  - µG
- ***Germany***
  - Institute for Applied Geodesy
- ***Japan***
  - Kyoto Electronics Manufacturing Company
- ***Russia***
  - State Research Centre of Russia (CSRI Elektropribor)
- ***Switzerland***
  - ETH-Zurich
- ***Finland***
  - Finnish Geopetic Institute
- ***Sweden***
  - Geodetiska

Other organizations that have active research programs are Scinrex, Carson Instruments, ZLS Corporation, Gravity Exploration Techniques Incorporated, Gravity Map Services, and µG. An example of a commercial application is a recently completed aerial survey of Switzerland by ETH-Zurich, using a LaCoste Romberg system coupled to GPS.

DATA SHEET III-16.2. GRAVITY GRADIOMETERS, NONMOBILE USE

Developing Critical Technology Parameter	In next 5 to 10 years: Static platform < 0.02 Eotvos/√Hz. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment to obtain static accuracy of sensor. Accelerometer axis align stations. SQUID sensors require superconducting temperature Dewars.
Unique Software	Algorithms and verified data for real time gravity compensation and detection (improvement > 10 to 1) for operation using arrays.
Technical Issues	All modern earthbound gravity gradiometers are affected by motion from all sources (seismic, acoustic, temperature, etc.) and require isolation/compensation. The problem is compounded by the need for measurements at different points near the test article.
Major Commercial Applications	Resource exploration. Detection of underground structures such as sink holes.
Affordability	Cost is proportional to usage. This is not a large-volume production technology.

RATIONALE

Gravity gradiometers are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for verticality for sensor stabilization.

The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity-meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. Data-base models developed from gravity gradiometer data are used by certain military platforms. This process was used by the Trident Missile System for stealth (nonradiating) positioning. Other applications include detection of underground structures, and nonintrusive identification of treaty-limited items. Gravity gradiometers have a higher military value than gravity meters because they have the ability to estimate vertical deflection in real time. Gravity gradiometers require stabilization and the associated software to maintain a stable reference frame.

Gravity gradiometers can detect underground structures and provide non-intrusive identification of treaty-limited items. Advanced systems will detect masses in the 300-m size at 200-m depths.

Relative to JCS Vision 2010, gravity gradiometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●●●	Brazil	●●	Canada	●●●●
China	●●●●	Czech Republic	●●●	Finland	●●●	France	●●●●
Germany	●●●●	Hungary	●●	India	●●●	Israel	●●
Italy	●●●	Japan	●●●●	Netherlands	●●	Poland	●●●
Romania	●●	Russia	●●●●	Slovak Republic	●●●	South Africa	●●
South Korea	●	Spain	●●	Sweden	●●●	Switzerland	●●●
Taiwan	●●●	UK	●●●●	Ukraine	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Lockheed Martin Corporation is the major U.S. company with proven capability. Other U.S. companies and research institutions include Bell Geospace and the University of Maryland.

Commercial interests are advancing the development and production of this technology. Few countries have elected to be dominant in gravity gradiometer technologies, while most are passive because of economic considerations. Researchers at Yale University are developing an atom interferometry-based gradiometer with a sensitivity potential of 1 Eotvos/√Hz using a 1-m baseline. Using a Superconducting Gravity Gradiometer, researchers at the University of Maryland have demonstrated 0.02 Eotvos/√Hz, while Gravitech in New Zealand is also developing a cryogenic gradiometer with potential sensitivity of 0.02 Eotvos/√Hz.

Countries of concern may not use (or develop) gravity gradiometers because of their technical complexity, high cost, and marginal military benefits. The alternative of using data from INS and GPS (or other aids) may prove to be more cost effective as a developing technology for data-base generation.

DATA SHEET III-16.2. GRAVITY GRADIOMETERS, MOBILE USE

Developing Critical Technology Parameter	In next 5 to 10 years: Moving platform < 5 Eotvos/√Hz. Continuing development of arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment to obtain mobile accuracy of < 5 Eotvos/√Hz. Accelerometer axis align stations.
Unique Software	Algorithms and verified data for real-time gravity compensation and detection (improvement > 10 to 1) for operation on mobile platforms, using arrays and time compensation, or both.
Technical Issues	All modern earthbound gravity gradiometers are affected by motion from all sources (seismic, acoustic, temperature, etc.) and require isolation/compensation. The problem is compound by the need for measurements at different points near the test article.
Major Commercial Applications	Resource exploration. Underwater terrain estimation. Detection of underground structures such as sink holes.
Affordability	Cost is proportional to usage. This is not a large-volume production technology.

RATIONALE

Gravity gradiometers are a POSITIME-influenced technology because of the interrelationship of gravity data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. Applications have been developed to correct, either directly or indirectly, for the local gravity disturbances or vertical deflection on a moving base/platform. The uncompensated vertical deflection is the largest error in many INS scenarios. The indirect—and most common—compensation technique uses vertical deflection map data computed from gravity-meter surveys. The direct method uses a gravity gradiometer for real-time compensation of the vertical deflection. In the latter mode, the spatial gravity gradients are multiplied (scalar product) by the velocity vector and integrated to obtain the vertical deflection in real time.

Another application for this technology is to use the gravity gradiometer in a map-matching mode for accurate position determination using previously surveyed map data. Due to roll off of the high frequencies in the gravity anomaly field with altitude, this accuracy could only be obtained at ground level and at low altitude, if then. Navigation at GPS accuracy through turns and acceleration is questionable, but the errors could perhaps be rectified afterward. These map-matching techniques using sensors giving data only along the flight path are questionable for long-term navigation, as there are likely to be areas where the data does not have adequate spatial variance to achieve this accuracy. In a local area, with proper conditions for the sensor type being used, these methods might be useful.

Gravity gradiometers with motion compensation provide a total covert undersea worldwide navigational capability using correlation techniques with gravity maps. The knowledge of instantaneous gravity conditions while on a moving platform is needed. Gravity gradiometers can detect underground structures and provide non-intrusive identification of treaty-limited items. Continuing development of gravity gradiometer arrays using advanced correlation techniques and very accurate clocks will improve the SNR of the array system. This is considered to be a militarily critical capability.

Gravity gradiometers have a higher military value than gravity meters because they have the ability to estimate vertical deflection in real time. Gravity gradiometers require stabilization and the associated software to maintain a stable reference frame. The resulting hybrid system has the potential to provide the military with a non-emanating, nonjammable, totally covert system that can be used worldwide for navigation. As noted, the system will require previously surveyed gravity map data, as well as a unique gravity signature that can be detected in the background noise. When there is not an adequate signature, the system maybe augmented with magnetic signature map matching (see subsection 16.4).

Another developing method of determining gravity is by computing the acceleration difference between an uncompensated INS and a GNSS. As measured by a GNSS, the computed acceleration of the platform is the pure acceleration of the vehicle, while the acceleration measured by an uncompensated INS contains the gravity vector and the platform acceleration vector. The difference is the gravity vector. Accurate time is required for compensation. A controlled vibration and acceleration environment is required to improve accuracy. Advanced filtering using optical correlators/processors and GNSS time synchronization are enabling technologies to obtain the gravity vector with better accuracy.

Relative to JCS Vision 2010, gravity gradiometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	China	●●●	Finland	●●	France	●●●●
Germany	●●	Hungary	●●	Italy	●●●	Japan	●●
New Zealand	●●	Russia	●●●	UK	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in gravity gradiometer technologies, while others are passive because of economic considerations. In moving-base instruments, several state-of-the-art gravity meters are currently being manufactured in the United States and Germany to yield mgal-level precision. State of the art in gravity gradiometers is on the order of 10 Eotvos/√Hz. This sensitivity is realized in the Lockheed Martin (formerly Bell) system, which is the only mobile system currently available. This system requires the use of very-high-grade accelerometers and is considered to be of military importance because the accelerometers are of higher grade than those found in most INS. Researchers at Yale University are developing an atom interferometry-based gradiometer with a sensitivity potential of 1 Eotvos/√Hz using a 1-m baseline. Gravitech in New Zealand is developing a cryogenic gradiometer with potential sensitivity of 0.02 Eotvos/√Hz. They are in the development stage, and the potential for moving base applications for either of these systems is unknown. An example of commercial application is a recently completed survey in the Gulf of Mexico by Bell Aerospace (Lockheed Martin). The survey used a three-dimensional, full tensor, gravity-gradient system derived from the Trident Missile System for positioning by use of undersea map data.

Countries of concern may not use (or develop) gravity gradiometers because of their technical complexity, high cost, and marginal military benefits. The alternative of using data from INS and GPS (or other aids) may prove to be more cost effective as a developing technology for data-base generation.

The following organizations have active research programs:

- ***United States***
  - Lockheed Martin
  - Yale University
- ***Germany***
  - Institute of Elecronic Basics of Computer Science
- ***Canada***
  - University of Vctoria
- ***New Zealand***
  - Gravitech

SECTION 16.3—RADIO AND DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS

Highlights

- With the discontinuance of the U.S. GPS Selective Availability (S/A)[1] and the use of Differential GPS (DGPS) combined with LORAN and improved LORAN, a navigation accuracy of less than 1 m (6 sigma)/0.3 m (SEP) can be provided to both friends and foes.
- Autonomous and common three-dimensional POSITIME grid reference will improve battlespace situational awareness by providing a precise POSITIME tag on all battlespace information collected to provide real-time knowledge of location and movement across battlespace of allied and enemy assets.
- Significant commercial and military growth and dependence on GNSS for position and time will increase as GNSS receivers decrease in cost, weight, and power.
- International GNSS (GLONAS, European Union 2, and Teledesic) capabilities will continue to be developed as alternatives to the U.S. GPS, as a means of providing better redundancy and integrity monitoring, or both.
- Increased combination of hybrid navigation and adaptive antenna systems will significantly reduce military dependence on GPS in a jamming combat environment or during signal loss. Future increased combinations of navigation, communication, imaging, and computer functions will improve situational awareness in urban terrain.
- Data-based referenced navigation technology, leveraged by increased computer speed and memory, will have increased commercial and military usage

.

OVERVIEW

Radio navigation, particularly GPS and LORAN, will continue to be used both by military and commercial users in the foreseeable future. Radio navigation continues to be the smallest and least expensive of the POSITIME systems. The ratio of commercial to military use of GPS and LORAN will probably be greater than 100:1. There is a definite trend to transition GPS from a DoD system to a commercial system. With S/A off, the 10 m accuracy will be available worldwide for all commercial users, who previously were limited to 100-m accuracy. The S/A had previously limited this 10 m accuracy to U.S. and allied military use only.

Another issue is the emergence of DGPS, which uses a small ground station outfitted with a GPS receiver whose geographic location is precisely determined, and the difference between surveyed and GPS position transmitted to another user. This procedure can provide an accuracy of better than 5 m. In Europe, a novel technique that transmits DGPS signals on an existing LORAN C, called Eurufix, has demonstrated position-fixing accuracy of better than 3 m. Localized jamming by friendly forces will deny these accurate GPS capabilities to an enemy only if the basic GPS signal is completely jammed. Antijam GPS components and systems, such as an adaptive antenna system, combined with high-speed digital signal processing (DSP) and a closely coupled hybrid GPS/INS will optimize antenna coverage patterns to specific signal and interference environments. This will produce an antenna pattern with nulls in the direction of broadband jammers very quickly. Better time accuracy (see Section 16.5) will allow rapid GPS direct-Y code acquisition, and the use of autonomous, low-power clocks will minimize GPS jamming and loss of satellite signal. In urban areas, loss of GPS signals due to signal blockage and multipath problems is a challenge to be overcome. Like all time difference of arrival (TDOA) systems, the LORAN system accuracy can be improved by more accurate clocks. Similar to GPS receiver improvements and miniaturization,

[1] President Bill Clinton, the White House, 1 May 2000

LORAN antenna and electronic miniaturization technology continues to improve LORAN receiver capability. Funding for continuation of LORAN ground stations because of the growing number of commercial applications continues to force the Federal Radio Navigation Plan to be revised, and the demise of LORAN is not as evident as it was 5 years ago.

Military GPS position accuracy will improve from 3 m to 1 m as a result of recent efforts to link the National Imagery Mapping Agency (NIMA) and the USAF GPS tracking networks, upgraded Kalman filtering, and reduced prediction error in broadcast navigation (NAV) messages. Using fixed location sites, DGPS can further improve the accuracy to less than 0.6 m. The use of DGPS, however, is currently limited to a localized area and the use of communications that may also be susceptible to jamming. Solar activity over the next 10 years is expected to cause problems in time transfer of 10–15 ns.

Technology related to radio ranging using normal tactical communication systems will be readily available for use in 5 years. The Army's enhanced position location system is representative of this technology. Communication signal-based ranging is a plausible method of positioning. Smart antenna techniques will be a catalyst, enabling commercial and military-based stations and user modes for personal communication systems (i.e., cellular telephones). This technology can provide a location accuracy approaching GPS.

Further GNSS improvements include:

- Upgrades to U.S. GPS/NAVSTAR capabilities to include incorporation of unencrypted C/A codes on L2, inclusion of third civilian frequency, inclusion of new encrypted military codes on L1 and L2, increase in transmission power, and potential increase in number of space vehicles.
- Integration of European Union Galileo public/private GNSS with the U.S. GPS system.
- Improvements in space vehicle orbital definition, increased ground station update frequency, and incorporation of more accurate ionospheric correction models on GNSS accuracy.
- Use of ground-based transmitters to provide wide area DGNSS corrections.
- Use of satellites (GEO and LEO) to provide wide area DGNSS corrections, particularly to aviation.
- Impact of FAA efforts to utilize DGNSS-based en-route and precision landing guidance through the WAAS and LAAS programs and the worldwide proliferation of compatible technology.
- The use of pseudolites (airborne and ground based) for military application and precision landing support (as envisioned in LAAS).

Further improvements to GPS accuracy, as well as reducing susceptibility to jamming, will be obtained by integration with the following Digital Terrain Data Based Navigation Systems:

- Digital Terrain Elevation Data (DTED)
- Digital Feature Analysis Data (DFAD)
- The World Geodetic System (WGS 84)
- The Earth Gravitational Model (EGM 96)
- The International Terrestrial Reference Frame (ITRF).

One of the deficiencies of GPS is that map referencing is not viable unless the receiver is moving to compute directional referencing (north). A magnetic compass or an INS is required for map referencing.

The Shuttle Radar Topography Mission (SRTM)1 will collect radar data over more than 80% of the earth. This is a major step toward the multi-Service requirement for Global DTED accuracy of 30 m by 2000. Table 16.3-1 shows the projected improvements in DTED accuracy.

Table 16.3-1. Comparison of Current and Projected Digital Terrain Elevation Data (DTED) Accuracy

	Absolute Horizontal	Absolute Vertical	Time Frame
Current DTED	50 m 90% CE	30 m 90% LE	Now
Expected DTED w/SRTM	20 m 90% CE	16 m 90% LE	2000+
Future Possibilities*	5–10 m 90% CE	5–10 m 90% LE	2015+

* Requires more accurate determination of the space vehicle's attitude/altitude for images.

DFAD contains feature data equivalent in feature content to a 1:250,000 scale topographic map. Because urban warfare at the brigade and individual soldier level requires higher resolution than current DTED and DFAD can provide, the U.S. Army's Training and Doctrine Command (TRADOC) Analysis Center provides higher resolution topographic maps (30-m elevation and a 1:50,000 scale or higher).[2]

Recent improvement in the EGM 96 has decreased absolute height uncertainty from 2–6 m (1 σ) to 0.5–1 m (1 σ) worldwide. This will benefit not only GPS but also INS accuracy. Figure 16.3-1 shows hybrid INS/GPS accuracy with use of geomapping data after loss of GPS. Closely monitoring WGS and ITRF has led to improvements in the level of agreement between WGS 84 and the ITRF, with the determination that they can now be considered equivalent.[3] While the GPS reference is WGS-84, the Russian GLONASS reference is PZ-90. The transformation model is developed and is being refined by the United States and Russians.[4]

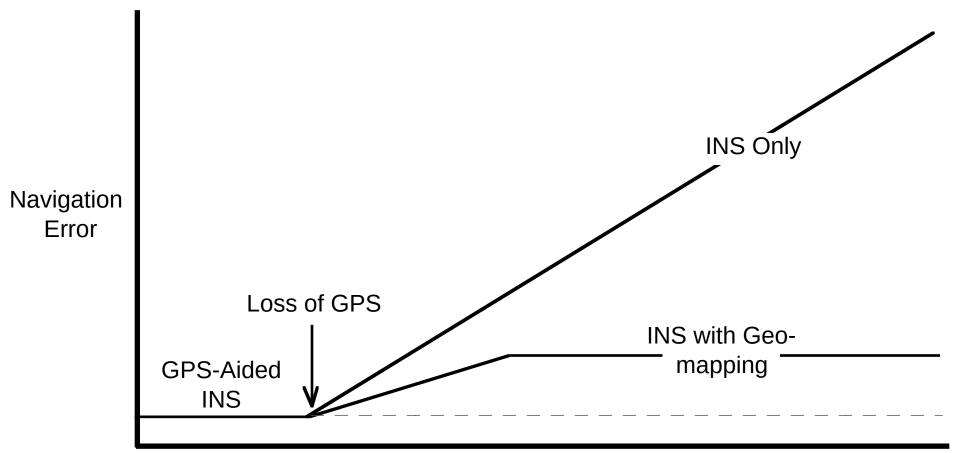

Figure 16.3-1. Hybrid INS Performance with Loss of GPS

The integration of three-dimensional digital terrain maps and other geo-mapping data [provided by NIMA and U.S. Geological Survey's National Mapping Division's Earth Resources Observation Systems (EROS)] with hybrid INS/GPS systems could subsequently provide highly accurate position, velocity, and track under dynamic and covert conditions, even after loss of GPS signals.

In addition, future improvements to three-dimensional digital map data could include global magnetic and gravity data. As a point of reference, given a gravity map having an accuracy of 1 Eotvos/√Hz) and resolution of 0.5 km, an aircraft flying at 200-m altitude at 360 km/hr constant velocity, having a 10 Eotvos/√Hz) gravimeter on board with a 0.0001 deg/hr drift rate gyro, could navigate with 5–10-m horizontal error and 5-m vertical error. All of these capabilities (by use of prestored ground and undersea terrain contour, acoustic, electromagnetic spectrum, magnetic, and gravity sensor data) will significantly increase the hybrid INS accuracy on a continuous basis to that currently provided by GPS at a rate of 1.0 Hz. PT&F form the baseline for telecommunications and navigation, and

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2 www.trac.army.mil/trandata.htr

3 *Refinements to the World Geodetic System*, 1984, by Stephen Malys, et al., NIMA.

4 *GPS World*, January 1999, p. 54.

its importance to military systems is becoming more evident with the operational use of the U.S. GPS (see Section 16.5).

Other data bases, such as bathymetric maps, are used by the United States and Russia to obtain submarine position fixes without surfacing. The process of generating the map consists of registering undersea bottom contours with GPS position data on a surface ship. This then becomes the data base for future map matching aboard a submarine. There are current studies exploring the feasibility of broad ocean bathymetry that would increase the number of available sites for position fixing.

RATIONALE

Accurate positioning, control, and redundancy for platforms are essential for effective coordination of military activities. Individual system accuracy depends on mission requirements. Encrypted signals of the GPS deny non-authorized users the full capability of the systems. Null-steerable antennas are a military response to jamming. Hybrid and DBRN systems combine the best features of different navigation systems to provide autonomous, covert, nonjammable information. DBRN technology is partially derived from sensor and Geographic Information Systems (GIS) technology. DBRN technology, leveraged by computer speed and memory, resolves data ambiguities and optimizes navigational sensor and stored data. Three-dimensional position ambiguities and other properties, such as magnetic and gravity signatures, will be resolved and optimized as stored geodetic data for navigation reference using sensors such as radar altimeters, magnetometers, gravity meters, and acoustic sensors. The use of power management and phase-shift key modulation reduces the emitted signal, resulting in a decreased detectability and covert (stealth) operation. Military uses for GPS will enhance the following:

- Supply location systems
- Spacecraft navigation
- Parachute insertion
- Air vehicle attitude
- Angle of attack
- Battlefield targeting
- Helicopter hover positioning
- Gravity measuring system
- HF communications frequency management
- Encryption/decryption
- DGPS
- Ship cargo management
- Situation awareness
- Minefield positioning
- Search and rescue
- Weather balloon navigation
- Power and communication line failures
- Inertial navigator reset and mapping
- System integration of sensors
- Pseudolite positioning system
- Position reporting for high-value assets
- AUV navigation
- Imaging
- Artillery smart round
- DGPS for heading
- Nuclear reset
- Construction

FAA's WAAS corrects the standard GPS signal to provide the accuracy, integrity, and availability needed for civil aviation navigation and precision approaches (Category 1) over a very large geographical area. Some of the critical functions include corrections for navigation satellite clock, satellite orbital data, and the effects of the ionosphere on the GPS and WAAS signals and ensuring the validity of WAAS messages. WAAS will use Geostationary satellites (space-based) transmitting GPS look-alike ranging signals, but with integrity messages and wide-area differential corrections. The LAAS is a ground-based augmentation system providing local area DGPS corrections. DGPS is based on providing corrections of errors that are common to both ground-based and aircraft receivers in the local area. LAAS has the capability of providing integrity using pseudolites (ground-based, low-powered satellites) and DGPS for accuracy of about 1 m on final approach and taxi. LAAS complements WAAS and will operate independently. For decades, the dismounted soldier's navigation tools have consisted of maps, compass, and individual pace count. Recently, GPS technology has been added to the tool set to improve position determination. Although a significant improvement, GPS can be jammed or blocked (terrain or man-made obstructions), and GPS does not provide accurate azimuth information at slow speeds for map north referencing.

Integrated navigation (INAV) technology introduces a new tool to help compensate for those times when GPS is either unavailable or unreliable—automated dead reckoning. INAV dead-reckoning capability is supplied by a dead-reckoning module (DRM), a small, low-power navigator consisting of an electronic compass and a pedometer using MEMS technology accelerometers.

WORLDWIDE TECHNOLOGY ASSESSMENT

The United States and Russia have independently developed and deployed GPS and GLONASS, respectively. These global systems and other proposed satellite systems are commonly referred to as GNSS. The United States leads the world in radio navigation and DBRN technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration with digital processing technology. The gap, however, is closing quickly, as the newer technologies require, in some cases, less capital investment in the technology. The European Union GNSS 2 system could be launched starting in 2003, providing accuracy of 5–10 m. Increased computational effectiveness for a given equipment volume and weight could provide an adversary with distinct navigation payoffs: (1) enhancing navigation capabilities and (2) improving reliability and resistance to hostile actions. Signal detection and processing technology is used to acquire, synchronize, and track desired signals for measurement of navigation parameters. The substantial margin of capability added by this technology is vital to continued U.S. superiority in precision navigation and the multitude of missions dependent thereupon. Highly interference-resistant receivers for satellite navigation systems are also vital. Militarily critical signal conversion technologies contribute directly to mission effectiveness by improved anti-jam performance; increased reliability; higher precision navigation; real-time adaptive response to hostile environments; and decreased system size, weight, and cost. The know-how to achieve improvements most beneficial to military applications depends upon integrated circuit technology and the software to support it. In this area, Russia lags the United States by 3 to 5 years. The worldwide growth of high-density semiconductor design and fabrication technology has been an enabling technology. From a control standpoint, however, the design technology is widely taught in universities and available in industry worldwide. Receivers that combine GPS and GLONASS technology are available on the commercial market from U.S. and non-U.S. manufacturers. Many of these receiver designs are for timing purposes rather than navigation. All of these receivers will provide a capability that has better jamming resistance, increased integrity, and higher accuracy than GPS or GLONASS systems alone. The UK, Germany, France, Israel, and Japan are also leading nations that have developed end-use products that use signals from both GPS and GLONASS and DBRN for military applications. The acquisition of dual-use end products could allow the transfer of the necessary know-how for military applications. Russia also has developed the use of magnetic arrays to improve compensation for DBRN systems (see subsection 16.4). Bathymetry maps are used by the United States and Russia to obtain submarine position fixes without surfacing. Improvements of GPS accuracy in generating those maps will enhance submarine undersea navigation without surfacing. Several countries, including the United States, UK, and France, use terrain databases for updating cruise missile inertial navigation accuracy.

Country	Radio Navigation Including Tele-communication	Data-Based Navigation (Terrain, Acoustic, Bathymetry, Electromagnetic Spectrum, Magnetic, Gravity, Stellar Referenced)
Australia	●●	●●●
Austria	●	●
Brazil	●●	●
Canada	●●●●	●●●
China	●●●	●●
Czech Republic	●●	●
Finland	●●	●
France	●●●●	●●●●
Germany	●●	●●●●
Hungary	●	●
India	●●●	●●
Israel	●●●●	●●●
Italy	●●●	●
Japan	●●●●	●●●
Netherlands	●●●	
Poland	●●	●●
Romania	●	●
Russia	●●●●	●●●
Slovak Republic	●	●
South Africa	●●●	●●
South Korea	●●	●●
Spain	●●	●●
Sweden	●●	●●
Switzerland	●●	●●
Taiwan	●●	●●
UK	●●●●	●●●●
Ukraine	●●●●	●●
United States	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.3-2. Radio and Data-Based Referenced Navigation Systems WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-16.3. RADIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS

DATA SHEET III-16.3. GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS)

Developing Critical Technology Parameter	In next 5 to 10 years: Signal decryption (antispoof) and/or null-steerable antenna, jamming protection; Accuracy (w/o S/A) of < 1 m 50% SEP in position and < 1 picosecond in time. < 0.1 m/s velocity for > 60,000 ft and for > 1,000 kts—lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Antispoofing (A-S); signal simulators and A-S < 1 picosecond measurement capability; electronic counter-countermeasures (ECCM) or interference resistance receivers.
Unique Software	Algorithms including classified, encrypted algorithms and verified data; vehicle attitude determination; direct Y-code algorithms verified through tests; A-S source code verified.
Technical Issues	Commercial A/C usage for autoland. GPS signal integrity; worldwide availability. Small accurate clocks that provide for direct acquisition of GPS Y code.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation, surveying. DoD has exclusive access to corrected U.S. GPS pseudorange, delta range, and ephemeris data.
Affordability	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs.

RATIONALE

Accurate positioning, control, and redundancy for platforms are essential for effective coordination of military activities. Individual system accuracy depends on mission requirements. With S/A discontinued[5], the 10 meter GPS accuracy will be available worldwide for all commercial users. Encrypted signals of the GPS deny non-authorized users the full capability of the systems. Null-steerable antennas are a military response to jamming. Hybrid and DBRN systems combine the best features of different navigation systems to provide autonomous, covert, nonjammable information. DBRN technology is partially derived from sensor and GIS technology. DBRN technology, leveraged by computer speed and memory, resolves data ambiguities and optimizes navigational sensor and stored data. The use of power management and phase-shift key modulation reduces the emitted signal, resulting in a decreased detectability and covert (stealth) operation.

FAA's WAAS corrects the standard GPS signal to provide the accuracy, integrity, and availability needed for civil aviation navigation and precision approaches (Category 1) over a very large geographical area. Some of the critical functions include corrections for navigation satellite clock, satellite orbital data, and the effects of the ionosphere on the GPS and WAAS signals and ensuring the validity of WAAS messages. WAAS uses Geostationary satellites (space-based) transmitting GPS look-alike ranging signals with integrity messages and wide-area differential corrections. The LAAS is a ground-based augmentation system providing local area DGPS corrections. DGPS is based on providing corrections of errors that are common to both ground-based and aircraft receivers in the local area. LAAS has the capability of providing integrity using pseudolites (ground-based, low-powered satellites) and DGPS for accuracy of less than 1 m on final approach and taxi. LAAS complements WAAS and will operate independently. The implementation of these functions combined with the growing reliance on GPS by the world commercial airline industry has created a special area of concern for military planners.

[5] President Bill Clinton, the White House, 1 May 2000

Joint Vision 2010 identifies long-range precision capability as a key factor in future warfare. GPS will provide increased accuracy and a wider range of delivery options. Advances in precise global positioning will provide the capability to determine accurate locations of friendly and enemy forces. Dominant maneuver and precision engagement will entail higher precision requirements, with longer ranges and more accurate targeting.

Military uses for GPS will enhance the following:

- Supply location systems
- Spacecraft navigation
- Parachute insertion
- Air vehicle attitude and angle of attack
- Battlefield targeting
- Helicopter hover positioning
- Gravity measuring system
- HF communications frequency management
- Encryption/decryption
- DGPS
- Ship cargo management
- Situation awareness
- Minefield positioning
- Search and rescue
- Weather balloon navigation
- Power and communication line failures
- Inertial navigator reset and mapping
- System integration of sensors
- Pseudolite positioning system
- Position reporting for high-value assets
- AUV navigation
- Artillery smart round
- DGPS for heading
- Nuclear reset
- Construction

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Brazil	●●	Canada	●●●●
China	●●●	Czech Republic	●●	Finland	●●	France	●●●●
Germany	●●	Hungary	●	India	●●●	Israel	●●●●
Italy	●●●	Japan	●●●●	Netherlands	●●●	Poland	●●
Romania	●	Russia	●●●●	Slovak Republic	●	South Africa	●●●
South Korea	●●	Spain	●●	Sweden	●●	Switzerland	●●
Taiwan	●●	UK	●●●●	Ukraine	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

GNSS research is being carried out throughout the world primarily because of the extensive commercial applications. At present, the United States, Russia, UK, Canada, France, and Japan appear to be leaders. China, India, and South Africa have recently made significant advances.

The following organizations have active research programs:

- ***United States***
  - Boeing
  - Interstate Electronics
  - Motorola
  - Rockwell
  - Sokkia
  - Garman
  - Magellan
  - Odetics
  - Trimble

- ***UK***
  - Skyforce Avionics
  - Synmetricon Navstar Systems, Ltd.
- ***Canada***
  - Canadian Marconi
  - Novatel
- ***France***
  - Dassault Sercel
  - Sextant Avionique
  - Thomson-CSF
- ***Germany***
  - Carl Zeiss Geodetic Systems
  - Datum GmbH
  - LITEF
- ***Spain***
  - Sena GPS SA
- ***Japan***
  - Furuno Electric Company
  - Koden Electronics Mitsubshi Industries
- ***Switzerland***
  - Leica
  - Micro-Blox AG
- ***Israel***
  - Elbit
  - Rokar International
- ***Australia***
  - Rojone Pty
  - Sigtec Navigation
- ***Italy***
  - Laben S.p.A.
- ***Taiwan***
  - San Jose Navigation

DATA SHEET III-16.3. DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEMS (DGNSS)

Developing Critical Technology Parameter	In next 5 to 10 years: Accuracy of < 0.3 m 50% SEP in position and < 1 picosecond in time; < 0.01 m/s velocity > 60,000 ft and > 1,000 kts—lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Algorithms including classified, encrypted algorithms and verified data; differential techniques that provide accuracy of < 0.3 m.
Unique Software	Algorithms including classified, encrypted algorithms and verified data needed to exceed military critical parameters; differential techniques that provide accuracy of < 0.3 meter; Algorithms that handle corrected pseudorange, delta range, and satellite start/stop position (corrected ephemeris) data and the source code for combining INS with GPS.
Technical Issues	Commercial aircraft usage for autoland. GPS signal integrity: worldwide availability of DGPS; accuracy enhancement.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation, and surveying.
Affordability	Accuracy and autonomy are the key cost drivers.

RATIONALE

DGPS uses a small ground station outfitted with a GPS receiver, the geographic location of which is precisely determined; the difference between surveyed and GPS position is transmitted to another user via a different frequency. This procedure can provide an accuracy of much better than 1 m. In Europe, a novel technique that transmits DGPS signals on an existing LORAN C, called Eurufix, has demonstrated position-fixing accuracy of better than 3 m.

Joint Vision 2010 identifies DGPS as a key technology to provide increased accuracy and a wider range of delivery options. Advances in precise global positioning will provide the capability to determine accurate locations of friendly and enemy forces. Dominant maneuver and precision engagement will entail higher precision requirements with longer ranges and more accurate targeting. The Joint Warfighting S&T Plan identifies DGPS as a key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

Military uses for DGPS will enhance the following:

- Supply location systems
- Spacecraft navigation
- Parachute insertion
- Air vehicle attitude and angle of attack
- Battlefield targeting
- Helicopter hover positioning
- Gravity measuring system
- HF communications frequency management
- Encryption/decryption
- Search and rescue
- Weather balloon navigation
- Power and communication line failures
- Inertial navigator reset and mapping
- System integration of sensors
- Pseudolite positioning system
- Position reporting for high-value assets
- AUV navigation
- Artillery smart round

- DGPS
- Ship cargo management
- Situation awareness
- Minefield positioning
- DGPS for heading
- Nuclear reset
- Construction

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Brazil	●●	Canada	●●●●
China	●●●	Finland	●●	France	●●●●	Germany	●●
Hungary	●	India	●●●	Israel	●●●●	Italy	●●●
Japan	●●●●	Netherlands	●●●	Poland	●●	Russia	●●●●
South Africa	●●●	South Korea	●●	Spain	●●	Sweden	●●
Switzerland	●●	Taiwan	●●	UK	●●●●	Ukraine	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States and Russia have independently developed and deployed GPS and GLONASS, respectively. The United States currently leads the world in radio navigation technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration with digital processing technology. The UK, Germany, France, Israel, and Japan are also leading nations that have developed end-use products that use signals from both GPS and GLONASS for military applications. The gap, however, is closing quickly, as the newer technologies require, in some cases, less capital investment in the technology. The European Union GNSS 2 system could be launched starting in 2003, providing accuracy of 5–10 m. Increased computational effectiveness for given equipment volume and weight could provide an adversary with distinct navigation payoffs: (1) enhancing navigation capabilities and (2) improving reliability and resistance to hostile actions. Signal detection and processing technology is used to acquire, synchronize, and track desired signals for measurement of navigation parameters. The substantial margin of capability added by this technology is vital to continued U.S. superiority in precision navigation and the multitude of missions dependent thereupon. Highly interference-resistant receivers for satellite navigation systems are also vital. Militarily critical signal conversion technologies contribute directly to mission effectiveness by improved anti-jam performance; increased reliability; higher precision navigation; real-time adaptive response to hostile environments; and decreased system size, weight, and cost. The know-how to achieve improvements most beneficial to military applications depends upon integrated circuit technology and the software to support it. In this area, Russia lags the United States by 3 to 5 years. The worldwide growth of high-density semiconductor design and fabrication technology has been an enabling technology. From a control standpoint, however, the design technology is widely taught in universities and available in industry worldwide. Receivers that combine GPS and GLONASS technology are available on the commercial market from U.S. and non-U.S. manufacturers. Many of these receiver designs are for timing purposes rather than navigation. All of these receivers will provide a capability that has better jamming resistance, increased integrity, and higher accuracy than GPS or GLONASS systems alone.

The following organizations have active research programs:

- ***United States***
  - Ashtech
  - Boeing
  - Garman
  - Interstate Electronics
  - Lockheed Martin
  - Northrop Grumman
  - Odetics
  - Rockwell
  - Trimble
  - Sokkia
- ***Canada***
  - Novatel
- ***Germany***
  - LITEF
- ***UK***
  - British Aerospace
  - Smith Industries
- ***Israel***
  - Elbit
- ***Japan***
  - Mitsubishi
- ***France***
  - Airbus Industries
  - SNECMA

DATA SHEET III-16.3. HYBRID RADIO NAVIGATION SYSTEMS (OTHER THAN INERTIAL NAVIGATION)

Developing Critical Technology Parameter	In next 5 to 10 years: Accuracy of < 1 m 50% SEP in position. Jamming protection < 0.01 m/s velocity > 60,000 ft and > 1,000 kts. For spacecraft—Pointing accuracy of < 10 arc sec—lighter and less expensive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment; GNSS receivers require special simulator testing systems. Specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters Source code for combining GNSS with Doppler, LORAN, or DBRN.
Technical Issues	Use of Doppler, acoustic (bathymetric), stellar, gravity sensing, or terrain data from data bases to improve GNSS/INS beyond uncompensated control level. Except for Doppler and acoustic, these methods are self contained, nonradiating, and non-jammable. The technical issues for radio ranging include multipath mitigation signal processing methods, low probability of detection waveforms, and low-power receivers.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation.
Affordability	Accuracy and autonomy are the key cost drivers.

RATIONALE

GPS accuracy will improve from 3 m to 1 m as a result of recent efforts to link the NIMA and the USAF GPS tracking networks, upgraded Kalman filtering, and reduced prediction error in broadcast NAV messages. Using fixed location sites, DGPS can further improve the GPS accuracy to less than 0.3 m. The use of DGPS, however, is currently limited to a localized area and the use of communications that may also be susceptible to jamming. Urban positioning is one outstanding military application of a hybrid system. In addition, hybrid GPS systems have better redundancy and integrity monitoring capabilities.

Like all TDOA systems, the LORAN system accuracy can be improved by more accurate clocks. Similar to GPS receiver improvements and miniaturization, LORAN antenna and electronic miniaturization technology continues to improve LORAN receiver capability. Funding for continuation of LORAN ground stations because of the growing commercial applications continues to force the Federal Radio Navigation Plan to be revised, and the demise of LORAN is not as evident as 5 years ago.

Radio ranging using normal tactical or commercial communications systems will be a mature technology within 5 to 10 years. This technology is likely to give a significant military advantage when GPS is jammed in future conflicts.

Further improvements to GPS accuracy, as well as reducing susceptibility to jamming, will be obtained by integration with other radio ranging systems and the following Digital Terrain Data-Based Navigation Systems:

- Digital Terrain Elevation Data (DTED)
- Digital Feature Analysis Data (DFAD)
- The World Geodetic System (WGS 84)
- The Earth Gravitational Model (EGM 96)
- The International Terrestrial Reference Frame (ITRF).

The integration of three-dimensional digital terrain maps and other geomapping data (provided by NIMA and U.S. Geological Survey's National Mapping Division's EROS) with Hybrid INS/GPS systems could subsequently provide highly accurate position, velocity, and track under dynamic and covert conditions, even after loss of GPS signals.

In addition, future improvements to three-dimensional digital map data could include global magnetic and gravity data. As a point of reference, given a gravity map having an accuracy of 1 Eotvos/√Hz and resolution of 0.5 km, an aircraft flying at 200-m altitude at 360 km/hr constant velocity, having a 10 Eotvos/√Hz gravimeter on board with a 0.0001 deg/hr drift rate gyro, could navigate with 5- to 10-m horizontal error and 5-m vertical error. All of these capabilities (by use of prestored ground and undersea terrain contour, acoustic, electromagnetic spectrum, magnetic, and gravity sensor data) will significantly increase the hybrid INS accuracy on a continuous basis to that currently provided by GPS at a rate of 1.0 Hz. PT&F form the baseline for telecommunications and navigation, and its importance to military systems is becoming more evident with the operational use of the U.S. GPS.

The United States and Russia uses other databases, such as bathymetric maps, to obtain submarine position fixes without surfacing. The process of generating the map consists of registering undersea bottom contours with GPS position data on a surface ship. This then becomes the database for future map matching aboard a submarine. There are current studies exploring the feasibility of broad ocean bathymetric maps that would increase the number of available sites for position fixing.

Joint Vision 2010 supports this technology by providing increased accuracy and a wider range of delivery options. Advances in precise global positioning will provide the capability to determine accurate locations of friendly and enemy forces. Dominant maneuver and precision engagement will entail higher precision requirements, with longer ranges and more accurate targeting. This technology also supports the Navy Plan for a precise navigation system. It is critical to provide a backup to GPS or to a successor system, once the GPS technology becomes obsolete.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Brazil	●	Canada	●●●●
China	●●●●	Czech Republic	●	Finland	●	France	●●●●
Germany	●●●●	Hungary	●	India	●●●	Israel	●●●●
Italy	●●●●	Japan	●●●●	Netherlands	●●●	Poland	●
Romania	●	Russia	●●●●	Slovak Republic	●	South Africa	●●●
South Korea	●●	Spain	●●	Sweden	●●	Switzerland	●●
Taiwan	●●	UK	●●●●	Ukraine	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States and Russia have independently developed and deployed GPS, GLONASS, and LORAN equivalent systems. The United States leads the world in radio navigation and DBRN technology and is progressively improving in the areas of accuracy, size, weight, reliability, cost, and integration with digital processing technology. The gap, however, is closing quickly, as the newer technologies require, in some cases, less capital investment in the technology. The European Union GNSS 2 system could be launched starting in 2003 providing accuracy of 5–10 m. Increased computational effectiveness for a given equipment volume and weight could provide an adversary with distinct navigation payoffs: (1) enhancing navigation capabilities and (2) improving reliability and resistance to hostile actions. Signal detection and processing technology is used to acquire, synchronize, and track desired signals for measurement of navigation parameters. The substantial margin of capability added by this technology is vital to continued U.S. superiority in precision navigation and the multitude of missions dependent thereupon. Highly interference-resistant receivers for satellite navigation systems are also vital. Militarily critical signal conversion technologies contribute directly to mission effectiveness by improved anti-jam performance; increased reliability; higher precision navigation; real-time adaptive response to hostile environments; and decreased system size, weight, and cost. The know-how to achieve improvements most beneficial to military applications depends upon integrated circuit technology and the software to support it. In this area, Russia lags the United States by 3 to 5 years. The worldwide growth of high-density semiconductor design and fabrication technology has been an enabling technology. From a control standpoint, however, the design technology is widely taught in universities and available in industry worldwide. Receivers that combine GPS and GLONASS technology are available on the commercial market from U.S. and non-U.S. manufacturers. Many of these receiver designs are for timing purposes rather than navigation. All of these receivers will provide a capability that has better jamming resistance, increased integrity and higher accuracy than GPS or GLONASS systems alone. The UK, Germany, France, Israel, and Japan are also leading nations that have developed end-use products that use signals from both GPS and GLONASS and DBRN for military applications. The acquisition of dual-use end products could allow the transfer of the necessary know-how for military applications. Russia also has developed the use of magnetic arrays to improve compensation for DBRN systems (see Section 16.4). Bathymetric maps are used by the United States and Russia to obtain submarine position fixes without surfacing. Improvements of GPS accuracy in generating those maps will enhance submarine undersea navigation without surfacing.

The following organizations have active research programs:

- ***United States***
  - Ashtech
  - Boeing
  - Garman
  - Interstate Electronics
  - Lockheed Martin
  - Northrop Grumman
  - Odetics
  - Rockwell
  - Trimble
  - Sokkia
- ***Canada***
  - Novatel
- ***Germany***
  - Daimler Chrysler Aerospace
  - LITEF
- ***UK***
  - British Aerospace
  - Smith Industries
- ***Israel***
  - Elbit
- ***Japan***
  - Mitsubishi
- ***France***
  - Airbus Industries
  - SNECMA
- ***Italy***
  - Piaggio Aero Industries

DATA SHEET III-16.3. LOW PROBABILITY OF INTERCEPT (LPI) RADAR ALTIMETERS

Developing Critical Technology Parameter	In next 5 to 10 years: Nondetectable in radar frequency range. Integrated with LPI limited-range, forward-looking sensor and terrain databases for better situational awareness in low-altitude terrain avoidance. Altitude accuracy: ± 1 foot at 0 to 5,000 ft. ± 25 feet at 5,000 to 60,000 ft.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Cross-correlation algorithms and verified data.
Technical Issues	Ability to determine height above terrain, as well as height above obstacle (i.e., trees and buildings). Expand technology to include Doppler navigation systems.
Major Commercial Applications	General aviation, particularly helicopters. However, commercial applications are very limited at this time.
Affordability	The all-digital approach will result in decreasing cost and increasing applications, including commercial.

RATIONALE

The use of power management and phase-shift key modulation reduces the emitted power of the radar altimeter system resulting in a decreased detectability and covert (stealth) operation. Altitude above ground is a critical parameter for military and commercial aircraft. LPI imaging radars use a millimeter-wave radar that is scanned to provide all-weather imaging. The application is for terrain following and landing approaches.

Joint Vision 2010 supports this technology because signature reduction will enhance the ability to engage adversaries anywhere in the battlespace and improve survivability of forces who employ it. The Joint Warfighting S&T Plan identifies LPI sensors as key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●	Germany	●●	Russia	●●	UK	●●●
United States	●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Worldwide research efforts of this technology is very limited due to its limited commercial applications. Currently, the UK appears to be the leader.

The following organizations have research programs:

- ***United States***
  - Honeywell
  - Litton
- ***UK***
  - GEC Marconi-Hazeltine

DATA SHEET III-16.3. DATA-BASED REFERENCED NAVIGATION SYSTEMS (Data-Based Digital Terrain, Acoustic, Bathymetric, Electromagnetic Spectrum, Magnetic, Gravity, and Stellar Referenced Navigation)

Developing Critical Technology Parameter	In next 5 to 10 years: Accuracy < 5- to 10-m grid accuracy.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data analysis algorithms and verified data.
Technical Issues	Data processing rate and throughput.
Major Commercial Applications	Ground vehicle navigation, aircraft navigation, ship and submersible navigation surveying.
Affordability	Lighter and less expensive will open more commercial applications.

RATIONALE

Further improvements to DBRNS is expected to provide an autonomous navigation capability, when GPS is jammed or unavailable (i.e., urban areas). The following are the key data bases that could provide improved accuracy with or without GPS, as an autonomous navigation or terminal guidance system:

- Digital Terrain Elevation Data (DTED)
- Digital Feature Analysis Data (DFAD)
- The World Geodetic System (WGS 84)
- The Earth Gravitational Model (EGM 96)
- The International Terrestrial Reference Frame (ITRF).

The SRTM will collect radar data over more than 80 percent of the Earth. This is a major step toward the multi-Service requirement for DTED accuracy of 30 m by 2000. Table 16.3-1 shows the projected improvements in DTED accuracy.

DFAD contains feature data equivalent in feature content to a 1:250,000 scale topographic map. Since urban warfare at the brigade-individual soldier level require higher resolution than current DTED and DFAD can provide, the U.S. Army's TRADOC Analysis Center provides higher resolution (30-m elevation and a 1:50,000 scale or higher topographic map).[6]

Recent improvement in the EGM 96 has decreased absolute height uncertainty from 2–6 meters (1 σ) to 0.5–1 meter (1 σ) worldwide. This will benefit not only GPS but also INS accuracy. Closely monitoring WGS and ITRF has led to improvements in the level of agreement between WGS 84 and the ITRF with the determination that they can now be considered equivalent.[7]

6 www.trac.army.mil/trandata.htr

7 *Refinements to the World Geodetic System*, 1984, by Stephen Malys, et al., NIMA.

Table 16.3-1. Comparison of Current and Projected Digital Terrain Elevation Data (DTED) Accuracy

	Absolute Horizontal	Absolute Vertical	Time
Current DTED	50 m 90% CE	30 m 90% LE	now
Expected DTED w/SRTM	20 m 90% CE	16 m 90% LE	2000+
Future Possibilities*	5–10 m 90% CE	5–10 m 90% LE	2015+

* Requires more accurate determination of the space vehicle attitude/altitude for images.

The integration of three-dimensional digital terrain maps and other geo-mapping data (provided by NIMA and U.S. Geological Survey's National Mapping Division's EROS) with hybrid INS/GPS systems could provide highly accurate position, velocity, and track under dynamic and covert conditions, even after loss of GPS signals.

The United States and Russia uses other databases, such as bathymetric maps, to obtain submarine position fixes without surfacing. The process of generating the map consists of registering undersea bottom contours with GPS position data on a surface ship. This then becomes the database for future map matching aboard a submarine. There are current studies exploring the feasibility of broad ocean bathymetric maps that would increase the number of available sites for position fixing.

Joint Vision 2010 supports this technology as part of precision navigation that will provide increased accuracy and a wider range of delivery options. Advances in precise navigation will provide the capability to determine accurate locations of friendly and enemy forces. Dominant maneuver and precision engagement will entail higher precision requirements, with longer ranges and more accurate targeting. The Navy plan also supports this technology for a precise navigation system other than GPS. It is critical to provide a backup to GPS, or a successor system, once the GPS technology becomes obsolete.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●●	France	●●●	Germany	●●●
India	●	Israel	●●	Italy	●	Japan	●●●
Russia	●●	South Africa	●	Sweden	●	UK	●●●
Ukraine	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United Sates, UK, Germany, France, and Japan are leading nations that have developed end-use products that use DBRN, particularly for commercial applications. The expected increased use of commercial vehicle navigation systems should increase the investment in more accurate DBRN systems worldwide. Military applications could build on the commercial investments.

Russia has developed the use of magnetic arrays to improve compensation for DBRN systems. The United States and Russia uses bathymetric maps to obtain submarine position fixes without surfacing.

The following organizations have active research programs:

- ***United States***
  - Boeing
  - Lockheed Martin
  - Northrop Grumman
  - Rockwell
- ***Germany***
  - LITEF

- ***UK***
  - British Aerospace
  - Smith Industries
- ***Israel***
  - Elbit
- ***Japan***
  - Mitsubishi
- ***France***
  - Airbus Industries
  - SNECMA
  - Thomson CSF

DATA SHEET III-16.3. GNSS ANTI-JAM COMPONENTS AND SYSTEMS (ADAPTIVE ANTENNA SYSTEMS)

Developing Critical Technology Parameter	In next 5 to 10 years: Fully integrated multiple-element antenna array and antenna electronics (e.g., signal processing unit). Interface to GPS receiver: RF or intermediate frequency (IF) signal. Creates nearly uniform hemispherical gain pattern when there is no external RF interference. Gain better than – 3.5 dB (over a 160-deg solid angle). Creates, in the presence of multiple RF sources, a null in the direction of unintentional or intentional interference signals. Null depth > 25 dB. Adaptive speed < 10 microseconds. Creates, in the presence of multiple RF sources, an antenna gain in the direction desired GPS satellite: gain > 10 dB. Overall processing gain: GPS receiver, antenna, and antenna electronics: > 61 dB total.
Critical Materials	Materials to implement low-observable requirements may or may not be used.
Unique Test, Production, Inspection Equipment	Test suppression capability verified at NAVSTAR GPS L2 or L1 frequencies. Test scenario(s) used GPS signal in space (SIS), or GPS signal simulator which generates the GPS wave front. (Simulated RF interference source injected or not injected in test scenario.) Operating bandwidth > 20 MHz (centered at L1 or L2). Characteristic or types of RF interference source used (i.e., wideband Gaussian, phase/frequency modulation, spread spectrum, pulse). Key characteristics of interference source or jammer: Range to receiver: 10 to 100 km. Effective radiated power: 10 mW to 100 kW. A signal line replaceable unit design that features a multiple-element antenna: an array of four elements, minimum.
Unique Software	Features validated null-steering, beam-steering, or beam-pointing algorithms. Features validated space-time adaptive processor (STAP) algorithm. Features validated space-frequency adaptive processor (SFAP) algorithms.
Technical Issues	Need a well calibrated antenna (i.e., gain and phase matching of antenna elements), small antenna size, digitization of anti-jam (AJ) components for cost reduction, efficient beamforming, improved receiver technology (i.e., more channels, better correlation). Premature release of military-exclusive interference suppression technology into non-military sector. Fundamental RF interference suppression research (and associated publications) reside in science/engineering work at academia or other science institutions. Research, coupled with know-how leads to formulation of information that exploits capabilities or weaknesses.
Major Commercial Applications	Commercial aviation, maritime, and land navigation. Telecommunications.
Affordability	Increased commercialization will significantly reduce cost.

RATIONALE

Anti-jam GPS components and systems, such as an adaptive antenna system, combined with high DSP and a closely coupled hybrid GPS/INS, will optimize antenna coverage patterns to specific signal and interference environments. This will produce an antenna pattern with nulls in the direction of broadband jammers very quickly. Better time accuracy or DSP techniques will allow rapid GPS direct-Y code acquisition, and the use of autonomous, low-power clocks will minimize GPS jamming and loss of satellite signal.

Space time adaptive processing (STAP) for anti-jam capability is an active research area. The technology is critical for optimizing adaptive antenna systems.

This technology is supported at the national level:

- Presidential Decision Directive NSTC-6 U.S. GPS Policy, March 1996.
- White House Office Science and Technology Policy and National Science and Technology Council report *The GPS: Assessing National Policies* by RAND, 1995.
- Congressional direction to DoD, National Academy of Sciences and the National Academy of Public Administration report *The GPS: A Shared National Asset: Recommendations for Technical Improvements and Enhancements*, 1996.
- Report, Defense Science Board Task Force on GPS (1995) and GPS Phase II, 1997.
- Report, U.S. Air Force Scientific Advisory Board, *GPS Survivability and Denial*, 1993.

The Joint Warfighting S&T Plan identifies GPS jamming as a limitation and anti-jam GPS technology as key to enabling rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●●	China	●●	Czech Republic	●●
France	●●●	Germany	●●●	India	●	Israel	●●
Italy	●●	Japan	●	Netherlands	●●	Norway	●
Russia	●●	South Africa	●	South Korea	●	Sweden	●
Taiwan	●	UK	●●●	Ukraine	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Anti-jam components are a critical military technology for use of satellite navigation systems in a high jamming environment. Anti-jam technology will be a high-cost component of GPS in the future. Many countries have expressed concern in multinational meetings about the low funding levels that are being projected to solve anti-jam problems of the future. Jamming of GPS can be deliberate or inadvertent in a high-electronics-activity environment. With more use of GPS as the primary navigation system, particularly for commercial aviation, this could increase commercial investment. Currently, the United States is the leader in this research.

The following organizations have active research programs:

- ***United States***
  - DARPA
  - Lockheed Martin
  - MIT Lincoln Labs
  - Northrop Grumman
  - Raytheon
  - USAF Research Labs

DATA SHEET III-16.3. GNSS ANTI-JAM COMPONENTS AND SUBSYSTEMS (ADAPTIVE NARROWBAND FILTERS)

Developing Critical Technology Parameter	In next 5 to 10 years: Receive, condition, and convert GPS RF signal to digital IF signal. Apply time, frequency, or amplitude-domain signal-processing techniques to remove interference signal that exists above thermal noise level. —Temporal (time) adaptive transversal filter performance 30 dB [narrow band (NB)]. —Spectral (frequency) digital excision filter performance 30 dB [continuous wave (CW)]. —Nonlinear amplitude domain processor performance 20 dB (CW).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Need to test against a representative jamming environment (i.e., wide variety of jammer signal characteristics and output powers).
Unique Software	None identified.
Technical Issues	Need a well calibrated antenna (i.e., gain and phase matching of antenna elements), small antenna size, digitization of anti-jam (AJ) components for cost reduction, efficient beam forming improved receiver technology (i.e., more channels, better correlation).
Major Commercial Applications	Commercial aviation, maritime navigation.
Affordability	Increased commercialization will significantly reduce cost.

RATIONALE

Anti-jam GPS components and systems, such as an adaptive antenna system, combined with high-speed DSP and a closely coupled hybrid GPS/INS will optimize antenna coverage patterns to specific signal and interference environments. This will produce an antenna pattern with nulls in the direction of broadband jammers very quickly. Better time accuracy and DSP will allow rapid GPS direct-Y code acquisition, and the use of autonomous, low-power clocks will minimize GPS jamming and loss of satellite signal.

This technology is supported at the national level:

- Presidential Decision Directive NSTC-6 U.S. GPS Policy, Mar 96.
- White House Office Science and Technology Policy and National Science and Technology Council report *The GPS: Assessing National Policies* by RAND, 1995.
- Congressional direction to DoD, National Academy of Sciences and the National Academy of Public Administration report *The GPS: A Shared National Asset: Recommendations for Technical Improvements and Enhancements*, 1996.
- Report, Defense Science Board Task Force on GPS (1995) and GPS Phase II (1997).
- Report, U.S. Air Force Scientific Advisory Board, *GPS Survivability and Denial*, 1993.

The Joint Vision 2010 and the Joint Warfighting S&T Plan identifies GPS jamming as a limitation and anti-jam GPS technology as key that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Canada	●●	China	●●	Czech Republic	●●
France	●●●	Germany	●●●	India	●	Israel	●●
Italy	●●	Japan	●	Netherlands	●●	Norway	●
Russia	●●	South Africa	●	South Korea	●	Sweden	●
Taiwan	●	UK	●●●	Ukraine	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Anti-jam components are a critical military technology for use of satellite navigation systems in a high jamming environment. Anti-jam technology will be a high cost component of GPS in the future. Many countries have expressed concern in multinational meetings about the low funding levels that are being projected to solve anti-jam problems of the future. Jamming of GPS can be deliberate or inadvertent in a high-electronics-activity environment. With more use of GPS as the primary navigation system, particularly for commercial aviation, this could increase commercial investment. Currently, the United States is the leader in this research.

The following organizations have active research programs:

- ***United States***
  - DARPA
  - Johns Hopkins (wideband)
  - Naval Research Lab
  - USAF Research Labs

Significant R&D is being conducted on narrow bandwidth and frequency agile filters to eliminate co-site and co-channel interference in communication systems. DARPA is investing in very narrow high-temperature superconducting filters with fixed frequency.

DATA SHEET III-16.3. MULTI-CHIP MODULE (MCM) TECHNOLOGY (GPS ON A CHIP)

Developing Critical Technology Parameter	In next 2 to 5 years: Will achieve GPS capability of less than 0.3 m. Ability to track 24 satellites. Dual frequencies. P-code and codeless. Receiver power consumption: < 150 mW. Signal and bandwidth processing power > 10X current commercial GPS receivers. Weight 0.5 kg.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Spread spectrum technology.
Technical Issues	Antenna designs and power level. Miniature antenna technology such as RFID may be a leveraging technology.
Major Commercial Applications	Commercial land, aviation, and maritime navigation. Cellular phone location, child locator system.
Affordability	Reduced size and increased commercialization will significantly reduce cost.

RATIONALE

This commercially driven electronics packaging technology will significantly reduce the cost of GPS receivers and provide a very affordable location awareness capability to any portable platform. The largest market of this technology is the car navigation system and telecommunications. Its usage is expected to quadruple by year 2001 and substantially reduce the cost of GPS receivers for both commercial and military use.

The foundation has been laid by research done under the DARPA Global Mobile program at Stanford University to enable the commercial version of GPS to be built on a chip using CMOS technology. Some further development is required, but it is likely that such a device could be available on the commercial market within 3 years.

The Joint Warfighters S&T Plan identifies GPS miniaturization as a key technology that will enable rapid target search and acquisition, battle coordination and target selection, and handoff and engagement for prosecution of time-critical targets.

There are no special requirements for the U.S. Government to gain access to this technology. This technology should be continuously monitored because of the substantial margin of capability added that is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●●	China	●	France	●●●	Germany	●●●
India	●	Israel	●●	Italy	●	Japan	●●●
Norway	●	Russia	●●	South Korea	●	Sweden	●
Switzerland	●●●	Taiwan	●	UK	●●●	Ukraine	●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

This is strictly a matter of economics. The fundamental technology for mixed linear and digital application-specific integrated circuits (ASIC) is well known and used throughout the semiconductor technology. The improvements in this area are, in fact, driven by the commercial telecommunications industry.

Research in this technology is present throughout the industrialized world. At present, the United States appears to be the leader.

The following organization have active research programs:

- ***United States***
  - Axiom Navigation
  - DARPA
  - Garman
  - General Dynamics
  - Genesis
  - Honeywell
  - Hughes
  - Interstate Electronics
  - Joint Propulsion Lab
  - Litton
  - Magellan
  - Motorola
  - Rockwell
  - SiRF Technology
  - Stanford University
  - Trimble
- ***Canada***
  - Canadian Marconi
  - Novatel
  - SiGEM
- ***Switzerland***
  - µbloxAG
- ***Taiwan***
  - LeadTek Research

SECTION 16.4—MAGNETOMETERS AND MAGNETIC GRADIOMETERS

Highlights

- Magnetometer and magnetic gradiometer technology varies with applications and cost. Anticipate more use of low-cost fiber-optic and torsion sensors for land-based usage and optically pumped technology for sea-based detection and classification.
- Magnetometer sensor arrays, a covert detection and classification technology, will be more viable because of accurate time sequencing, computer speed, and memory advances, providing increased detection and location of submarines, mines, and mobile missiles.
- Knowledge of position, GNSS time, and better computational capabilities using optical processing/ correlation will greatly enhance magnetic array detection performance.
- Newly developed potassium and helium-4 optically pumped magnetometers are demonstrating performance comparable to superconductive quantum interference device (SQUID) magnetometers at low cost. Medical research and diagnostics is major funding source for future of SQUID sensors and possibly for potassium, if sensor can be reduced in size. Magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminate the natural geomagnetic background noise.
- High T_c SQUID technology has matured since its inception in 1987 to the point where nitrogen-cooled superconducting sensors are rivaling their low T_c counterpart. Use of giant magnetoresistive (GMR) sensors is projected for a number of applications for which cost, size, and power are driving factors.
- Magnetic sensor use for nondestructive testing and inspection of vehicle integrity will increase.

OVERVIEW

Magnetometers and magnetic gradiometers are of interest to the military because of their covert detection, signature classification, and position determination capability. Although magnetic sensing of direction is thought to be of secondary use by the military, there is a need to provide low-cost map referencing of magnetic north and to maintain magnetic databases using magnetic sensors. Magnetic heading can be sensed by a flux value, for instance, or computed by subtracting magnetic variation from the true heading sensed by an INS. Magnetic variation is obtained from a map data base and can be used in many formats and accuracy levels. The use of true heading vice magnetic heading by the majority of navigation applications has been vastly increased by the quantities of INS and GPS in military and commercial applications in the past 10 years. Using computational techniques, data bases with prior or real-time magnetic field data from magnetometer arrays can be used to reduce the spatial and temporal background noise in the detection of land vehicles, submarines, or mines. Increasing the signal-to-noise ratio of magnetic sensors is a major factor in improving magnetic applications by the military. Both the development technology and the production technology are military critical. Magnetic sensor types of special interest include fluxgate, SQUID, nuclear precession, optically pumped, fiber-optic, and induction coil. Figure 16.4-1 provides a comparison of the current spectral density and frequency range of these sensor types. Figure 16.4-2 provides a projected capability for these sensors within the next 15 years.

The performance possible with the more sensitive SQUID, optically pumped, and induction-coil technologies will improve, and the cost and size of these sensors will come down. At the same time, other technologies that have demonstrated limited performance in comparison to the superconducting and total-field technologies will probably become competitive. Thin-film GMR sensor technology appears at present to provide a most promising possibility (see Figure 16.4-2). Using GMR technology, nonvolatile random access memory will have lower power consumption and faster access speeds. GMR circuits, transformers, and logic gates are also viable.

For details on mine countermeasures, see Section 17.7.

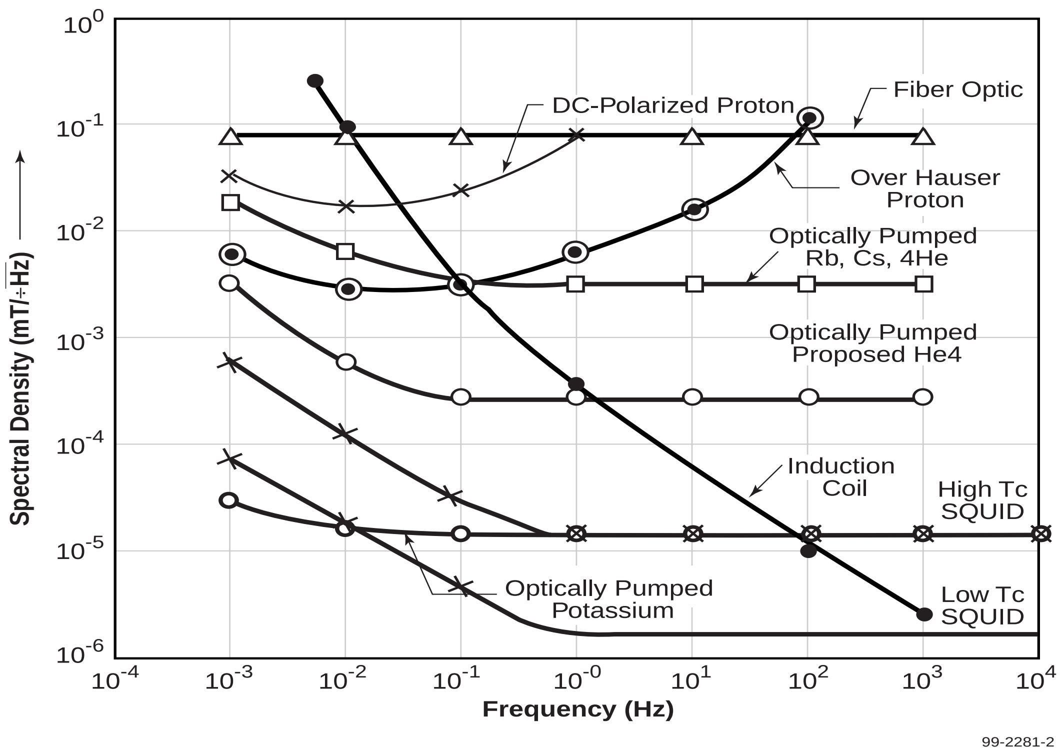

Figure 16.4-1. Comparison of the Current Spectral Density and Frequency Range of Various Sensors

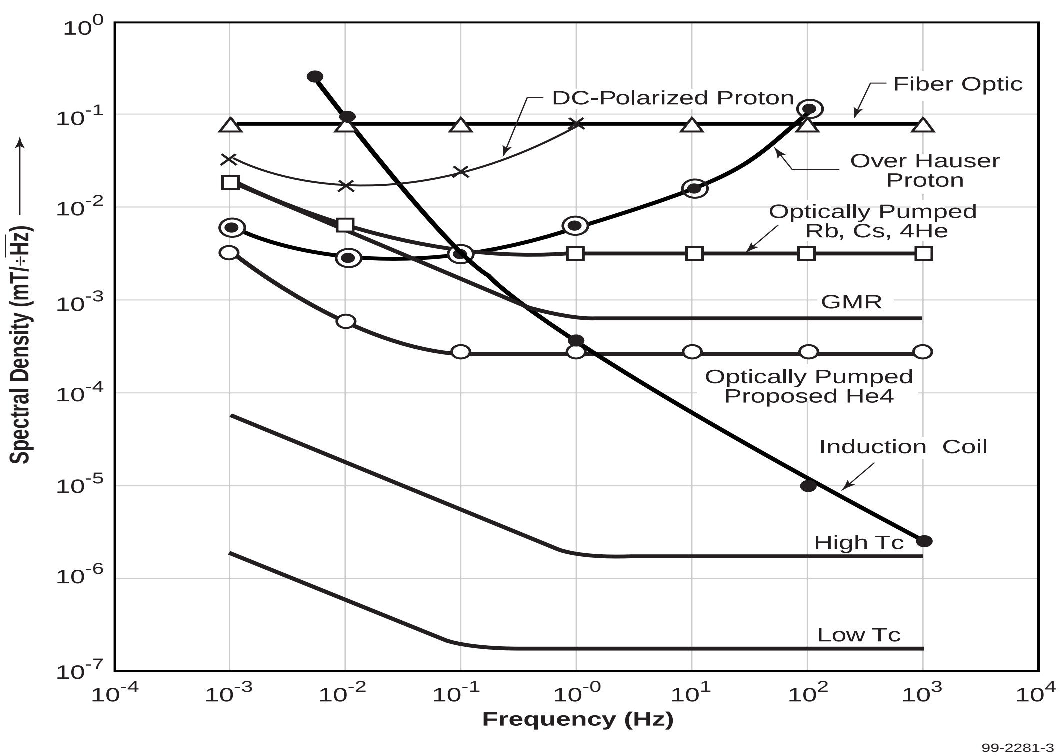

Figure 16.4-2. Comparison of Projected Spectral Density and Frequency Range of Various Sensors

On the one hand, the sensitivity of these sensors will likely increase, and applications involving multiple units of low-cost, short-range, remote sensors will evolve. Active electromagnetic detection of a target illuminated by a low-frequency magnetic or electrical-current source, currently utilized for land mine detection, will likely be utilized in a wider range of applications as underlying sensor technology and signal processing capabilities improve. Further advances in microelectronics, most significantly in the area of high dynamic range, multichannel, analog-to-digital converter technology and DSP, will enhance capabilities and significantly reduce cost and complexity of the underlying sensor technologies. These factors will make concepts involving multiple units of low-cost, short-range distributed sensors more attractive. Similarly, advancements in microelectronics will increase magnetic-sensor capabilities on-board magnetically noisy platforms through large-scale use of distributed sensors monitoring the platform noise.

RATIONALE

Magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for anti-submarine warfare, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. Magnetic sensors in a tactical missile can be used to detect and localize a target, such as a tank, from the background magnetic field variations.

Another application is to determine position for navigational purposes relative to a database containing previously surveyed magnetic field information. Deployment of additional magnetic observatories in open ocean areas will permit magnetic models to be developed with 1-deg RMS magnetic variation worldwide, and the possibility of reduction to 0.5 by 2015 exists. Dual-use applications include clinical diagnostics and geophysical applications. Commercial users may adapt the use of magnetometer arrays, but the main initial (developing) application is military. Ocean bottom arrays, as depicted in Figure 16.4-3, can be used to detect and classify vessels. Land-based arrays, as depicted in Figure 16.4-4, can measure time-varying natural noise for airborne compensation. Of special concern are compensation methods for platform motion and other self-induced magnetic noise. The main differences between military and commercial use are the real-time accuracy requirements for operation from a moving base and the detection and classification capability. There has not been significant progress in advancing the state of the art of magnetic sensors in the past decade, with the possible exception of the development of the potassium optically pumped sensor. The experimental results for the potassium sensor gives a magnetic sensor noise level of 10 microgamma (10^{-14} tesla rms) per $\sqrt{\text{Hz}}$. Work continues on further development of this new class of sensor. Before the advent of these potassium sensors, the instrument noise level for the best optically pumped magnetometers was about 3×10^{-12} tesla rms per $\sqrt{\text{Hz}}$, about two orders of magnitude inferior to the newly developed potassium sensors. Potassium gradiometer accuracy now equals SQUID capabilities, but without the low-temperature logistic and motion problems of SQUIDS. SQUIDS are vector devices and more susceptible to motion-induced effects. A potassium gradiometer is a scalar device, and an RMS noise of 10 microgammas/meter (or 10^{-14} tesla/meter) at 10-second periods has been achieved. Potassium gradiometer technology permits near elimination of time-varying geomagnetic noise. Laser pumping will improve accuracy by a factor of 2 to 3.

During the last decade, multiple-channel, short-baseline tensor gradiometers utilizing low-critical-temperature (low T_c) SQUIDs have been deployed from underwater tow systems and have demonstrated an effective means to detect, localize, and classify sea mines and exploded ordinance. During the same timeframe, a high T_c SQUID technology utilizing liquid nitrogen for cooling has matured. High T_c sensors are of interest for military applications because nitrogen cooling reduces logistic issues and permits smaller package sizes, compared to low T_c SQUID sensors that require liquid helium for cooling. Significant progress in this technology has been made. High T_c magnetometers have demonstrated sensitivities of 100 microgamma (10^{-13} tesla) per $\sqrt{\text{Hz}}$ at 0.1 Hz. This figure should be compared to the performance of 10 microgamma per $\sqrt{\text{Hz}}$ at 0.1 Hz that has been reported for both low T_c superconducting magnetometers and potassium optically pumped magnetometers. Further sensitivity increases are expected as high T_c manufacturing technology improves.

For tracking and homing applications in which less sensitivity is acceptable, but cost, size, weight, and logistics are important factors, a multichannel tensor gradiometer has been developed using fluxgate technology. This fluxgate gradiometer is especially useful for providing precise localization in man-portable operations.

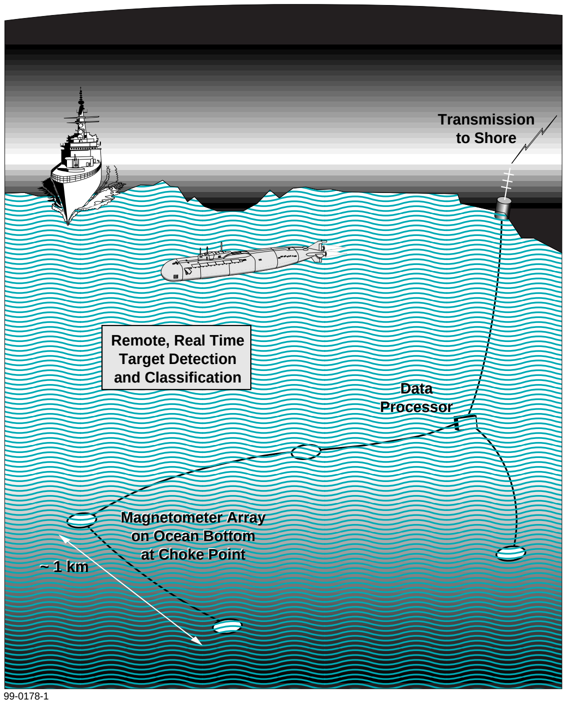

Figure 16.4-3. Ocean Bottom Arrays

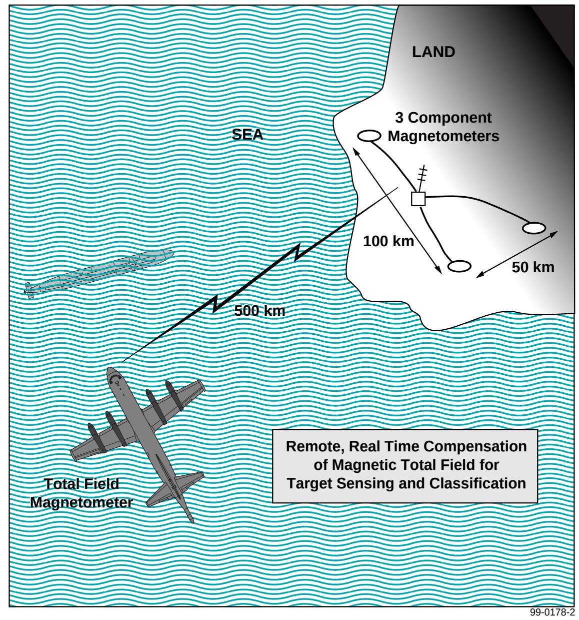

Figure 16.4-4. The Remote Real-Time Compensation Process

The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. There are four scenarios that will illustrate this potential improvement:

1. **Fixed Array of Sensors.** When a fixed array of sensors is used on the ground or underwater, the increased knowledge of position and time are coupled to enhance the computation power because of the synergistic effect of the array. The spectral energy density functions for environmental noise can be precisely deduced. Then, in the presence of a signal of interest, the special density function of the magnetic signatures of interest can be extracted from background noise and thus provide an improved SNR than that realizable without the use of energy spectral density techniques. For instance, arrays of three component magnetometers on land or on the ocean bottom have the potential of reducing time-varying geomagnetic background “noise” by 80 percent or more. This time-varying magnetic background noise is a major impediment to detection of the magnetic anomaly signals from mines or submersibles, depending upon the operational scenario (sensor noise, geology motion, etc.). By placing three to five magnetometers at distances of 10 to 100 kilometers, gradients and amplitudes of natural pulsations may be measured. By using previously determined transfer functions (based on geologic structure and experiment), the pulsation field may be extrapolated to a distant point at sea. The predicted field for the distant point may be telemetered to an antisubmarine warfare (ASW) aircraft. These predicted fields may be subtracted from the airborne magnetometer output in near real time to significantly increase the signal-to-noise ratio and permit detection of submarine magnetic anomaly signals at greater ranges. Figure 16.4-4 is a graphic display of the remote real-time compensation process.

2. **Moving Array of Sensors.** If the magnetometry system consist of one or more moving sensors towed behind a ship or plane, the ability for precise position, orientation, altitude (or depth), etc., of the various sensors can be deduced and the background noise spectral density determined. This will enhance the signal-to-noise ratio determination of targets of interest.

3. **Target Recognition.** With the enhanced knowledge of location and orientation of the various sensor(s) when the sensor(s) and target(s) are in relative motion, the SNR will be enhanced as pointed out above. For

a typical ASW application, the sensors are remote from the target, and thus the target can be treated as a simple dipole and the "inverse problem," that is, deducing the location and moment of the target(s) of interest from the magnetic field contours, is relatively straightforward. However, in those scenarios when the target and sensors are nearby (that is, when the length of the target or the lateral dimensions of the sensor array are comparable to or less than the distance between target and sensor array), the target must be represented by dipole as well as higher order poles. In this case, the extraction of the magnetic signature from the magnetic field contours is very demanding on computation power, requiring precise information about the sensor position, orientation, etc. Thus, the future development of "smart" magnetic sensor systems requires precise position and time information as well as massive computation capabilities.

— The ability to increase knowledge of locations, time, etc., in packages that can be utilized in cost-effective magnetic sensors and sensor arrays is very crucial to these enhanced magnetometer systems.

— The development of computers with enhanced capability (both speed and memory) and with very low power consumption is crucial for the maturing of these enhanced magnetic detection systems.

4. **Submarine Electric Fields.** Dissimilar metals or differences in surface properties of the same metal give rise to "corrosion" currents flowing in salt water in the vicinity of a submarine. The currents produce a static electric dipole aligned with the longitudinal axis of the submarine. This is called the "submarine electric dipole moment" and is quite variable. The dipole moment, in turn, produces a magnetic field. This electric dipole-produced (EDP) magnetic field falls off as the inverse square of distance, unlike the well-known "hull anomaly" magnetic field, which falls off the inverse cube of distance. This means that, although the EDP magnetic anomaly has a smaller magnetic moment than the hull anomaly, at some distance the magnetic field from the electric dipole will begin to get larger than that from the hull moment. In the past, magnetometers were not sensitive enough to detect this EDP magnetic field anomaly, but the advent of the potassium magnetometer means that it may be detectable.

   The same "corrosion" currents are modulated by differences in electrical resistance between the journal bearings and the propeller shaft as rotation occurs. The modulation will be at the shaft rotation rate and its multiples. This phenomena gives rise to an oscillating electromagnetic field which propagates through the water and into the air [extremely low-frequency emission (ELFE) signal]. The high sensitivity of the potassium magnetometer promises much greater range for the detection of this signal.

WORLDWIDE TECHNOLOGY ASSESSMENT

Depending on military and commercial uses, many countries, such as France, Germany, Canada, Russia, and the Ukraine, have developed a capability in most of the differing magnetometer and magnetic gradiometer technologies. Canada leads the world in fluxgate sensors; Russia has developed a unique potassium-resonance magnetometer capability; the United States leads in SQUID development for military; and Japan, Russia, Ukraine, and Germany lead in civil clinical applications. A joint Russian, Canadian, and U.S. team has built optically pumped potassium magnetometers and gradiometers. The potassium magnetometer is based on a preliminary design originally funded by the Soviet Navy in the late 1980's. This magnetometer has achieved noise levels comparable to SQUIDs. The potassium magnetometer does not suffer from the requirement for cryogenic support systems and motion compensation techniques of SQUIDs. This potassium magnetometer should be considered a critical development because the nation deploying it for submarine detection will enjoy a noise level 3 orders of magnitude less than that of systems deployed by the U.S. Navy and others. This translates to a possible 10-fold increase in detection range. When employed as a gradiometer, it has the advantage of near cancellation of time-varying geomagnetic background noise (geomagnetic pulsations). The rms noise level of a single potassium magnetometer has been measured as 14 microgammas (14 femto tesla) at 0.1 Hz. The noise level of a 2-m gradiometer is 10 microgammas (10 femto tesla) per meter at 0.1 Hz. These measurements were made with two complete gradiometers operating side by side in the real Earth field. In an experiment conducted at Kavgolovo (a test site northeast of Saint Petersburg, Russia) it was shown that laser pumping (versus lamp pumping) could further reduce the noise by a factor of 3. Relative to ELFE, propeller-shaft rotation modulates corrosion currents in the 3- to 20-Hz range. Russia has deployed sensors on the ocean bottom and detected this phenomenon. China and Japan have limited but expanding capabilities in several magnetometer technologies. Although the United States leads in platform motion compensation, Russia appears to have the lead in the use of compensation using magnetic sensor arrays.

Country	Magnetometers	Magnetic Gradiometers
Australia	●●	●●
Austria	●●	●
Brazil	●	●
Canada	●●●	●●●
China	●●	●
Czech Republic	●	●
Finland	●●●	●●●
France	●●●	●●●
Germany	●●●	●●●
Hungary	●	●
India	●●	●●
Israel	●●●	●●●
Italy	●●	●●
Japan	●●●	●●●
Netherlands	●●	●●
Poland	●	●
Romania	●	●
Russia	●●●	●●●
Slovak Republic	●	●
South Africa	●●	●●
South Korea	●●	●●
Spain	●●	●●
Sweden	●	●
Switzerland	●●	●●
Taiwan	●	●
UK	●●●	●●●
Ukraine	●●	●●
United States	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.4-5. Magnetometers and Magnetic Gradiometers WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-16.4. MAGNETOMETERS AND MAGNETIC GRADIOMETERS

DATA SHEET III-16.4. SQUID MAGNETOMETERS

Developing Critical Technology Parameter	In next 5 to10 years: Noise level < 0.03 nanotesla (nT) rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Low noise level; field deployment problems; requires cryogenic environment; magnetic contamination. Commercial technology suitable for military application.
Major Commercial Applications	Resource exploration, nondestructive testing, and medical imaging.
Affordability	Medical imaging is funding driver.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. SQUID magnetometers, in particular, are very accurate. They are key elements of magnetic anomaly detectors and covert detection and are used in ASW, mine hunting, geology, area surveillance, threat classification, and nondestructive testing. They have an inherent logistic requirement for a cryogen, liquid helium, or liquid nitrogen for superconducting operation.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The emergence of precise location and time information during the last decade and the availability of greatly enhanced computation capabilities has improved the effectiveness of these magnetometry systems. During the last decade, multiple-channel, short-baseline tensor gradiometers, utilizing low T_c SQUIDs cooled by liquid helium, have been deployed from underwater tow systems and have demonstrated an effective means to detect, localize, and classify sea mines and exploded ordinance. During the same time frame, a high T_c SQUID technology utilizing liquid nitrogen for cooling has matured. This problem of low-temperature operation also introduces the self-generated noise of the cooling device or method. SQUIDS are vector devices which can be packaged into compact, multichannel, tensor gradiometers capable of precise localization and classification as compared to total-field sensors. Because they are vector devices, they are more susceptible to motion-induced effects. Approaches have been developed and demonstrated to compensate for both sensor-intrinsic and motion-induced noise to obtain operational usefulness with extreme accuracy. High T_c sensors are of interest for military applications because nitrogen cooling reduces logistic issues and permits smaller package sizes than required for low T_c SQUID sensors, which require liquid helium for cooling. The development of nonmagnetic closed-loop refrigerators will eventually eliminate the logistic tail for passive nitrogen cooling. Significant progress in high T_c technology has been made. High T_c magnetometers have demonstrated sensitivities of 100 microgamma (10^{-13} tesla) per √Hz at 0.1 Hz. This figure should be compared to the performance of 10 microgamma per √Hz at 0.1 Hz that has been reported for both low T_c superconducting magnetometers and potassium optically pumped magnetometers. Further sensitivity increases are expected as high T_c manufacturing technology improves.

Relative to JCS Vision 2010, SQUID magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●	Brazil	●	Canada	●●●
China	●	Denmark	●●	Finland	●●●	France	●
Germany	●●●●	Hungary	●	India	●	Israel	●
Italy	●●	Japan	●●●	Netherlands	●●	Poland	●
Romania	●	Russia	●●	Slovak Republic	●	South Africa	●
South Korea	●●	Spain	●	Sweden	●	Switzerland	●
Taiwan	●	UK	●●●	Ukraine	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present, the United States and Germany appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - Magnesonsors
  - Quantum Design
  - Tristan
- ***Canada***
  - Canadian Thin Films
- ***Germany***
  - Julicher SQUID G.m.b.H.
  - FIT Messtechnik GmbH
- ***Denmark***
  - NKT
  - Nonlinear Dynamics Group at University of Denmark

DATA SHEET III-16.4. MAGNETOMETERS—ELECTRON RESONANCE AND OPTICALLY PUMPED

Developing Critical Technology Parameter	In next 5 to10 years: Noise level < 0.03 nT rms/√Hz. Sensitivity 0.005 nT Resolution 0.01 nT
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Indirect detection measurement of Earth's electric field. Potassium sensors equal to SQUID accuracy without logistic complication of low-temperature requirements. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There have been major advances in the development of electron resonance and optically pumped magnetometers. In a gradiometer configuration, with one magnetometer at each wing tip of an aircraft, an optically pumped magnetometer can provide not only target detection, but can also indicate the position of a target with respect to the aircraft. This offers a tremendous operational advantage over single-magnetometer systems.[1]

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The emergence of precise location and time information in the past decade or so and the availability of greatly enhanced computation capabilities have improved the effectiveness of these magnetometry systems. The experimental results for the potassium sensor gives a magnetic sensor noise level of 10 microgamma (10^{-14} tesla rms) per √Hz. Work continues on further development of this new class of sensor. Before the advent of these potassium sensors, the instrument noise level for the best optically pumped magnetometers was about 3×10^{-12} tesla rms per √Hz, about two orders of magnitude inferior to the newly developed potassium sensors. Potassium gradiometer accuracy now equals SQUID capabilities, but without the low-temperature logistic and motion problems of SQUIDS. Because of their accuracy potential, electron resonance and optically pumped magnetometers have applications such as covert detection area surveillance and threat classification. In addition, He4 sensors using laser pumping have been developed and demonstrated to have performance of 3×10^{-13} tesla rms per √Hz. These sensors are key elements of magnetic anomaly detectors and can be used in ASW, mine hunting, geology, and nondestructive testing.

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1 www.rmsinst.com/ct2.htm, July 8, 1999.

Relative to JCS Vision 2010, electron resonance and optically pumped magnetometers have application in precision engagement. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●●	Brazil	●	Canada	●●●●
China	●●●	Czech Republic	●	Finland	●●	France	●●●
Germany	●●●	Hungary	●●	India	●	Israel	●●●
Italy	●●	Japan	●●	Netherlands	●●	Poland	●●
Romania	●	Russia	●●●●	Slovak Republic	●	South Africa	●●
South Korea	●	Spain	●	Sweden	●●	Switzerland	●●
Taiwan	●	UK	●●●	Ukraine	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present, the United States, Russia, and Canada appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - Geometrics
  - Geophysical Research Institute (University of New England)
  - Polyatomic
  - Raytheon Systems (formerly Texas Instruments)
- ***Canada***
  - GEM Systems
  - Sander Geophysics Limited
  - Scintrex
- ***Russia***
  - URALS State Technical University (Laboratory of Quantum Magnetometry)
- ***UK***
  - AROLAB (Oxford University)
- ***China***
  - Ministry of Geology and Mineral Resources

DATA SHEET III-16.4. MAGNETOMETERS—NUCLEAR PRECESSION

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level < 0.03 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Magnetic contamination. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of magnetic sensors in the past decade. Nuclear procession magnetometers have covert detection capability and are key elements of magnetic anomaly detectors, area surveillance, and threat classification. Other applications include ASW, mine hunting, nondestructive testing, and geology. Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization.

Relative to JCS Vision 2010, nuclear procession magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●●	Brazil	●	Canada	●●●●
China	●●	Czech Republic	●	Finland	●●	France	●●●
Germany	●●●	Hungary	●●	India	●	Israel	●●
Italy	●●	Japan	●●	Netherlands	●●	Poland	●●
Romania	●	Russia	●●●	Slovak Republic	●	South Africa	●●
South Korea	●	Spain	●	Sweden	●●	Switzerland	●●
Taiwan	●	UK	●●●	Ukraine	●●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present, Canada appears to be the leader.

The following organizations have active research programs:

- ***United States***
  - Geometrics
  - Raytheon Systems
- ***Canada***
  - GEM Systems
  - Scintrex
- ***Russia***
  - URALS State Technical University (Laboratory of Quantum Magnetometry)

DATA SHEET III-16.4. MAGNETOMETERS—INDUCTION COIL

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level < 0.03 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Low noise level reduction of magnetic contamination, normally used for stationary applications. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of this magnetic sensing technology in the past decade.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Induction coil magnetometers have the greatest change of spectral density over a wide frequency range than all other magnetic sensors (see Figure 16.4-1 for details). They are used in ASW, mine hunting, geology, covert detection, area surveillance, nondestructive testing and threat classification. Triaxial magnetic induction magnetometers have been integrated with biaxial (leveling) inclinometers to provide low-cost compass heading, pitch and roll with a 10-nT resolution. Further research in computation techniques should improve the accuracy. This capability, when hybridized with sonar array detectors, is being applied to self-contained underwater breathing apparatus (SCUBA) marine research and detection.

Relative to JCS Vision 2010, induction-coil magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Brazil	●	Canada	●
China	●	Czech Republic	●	Finland	●	France	●
Germany	●	Hungary	●	India	●	Israel	●
Italy	●	Japan	●	Netherlands	●	Poland	●
Romania	●	Russia	●	Slovak Republic	●	South Africa	●
South Korea	●	Spain	●	Sweden	●	Switzerland	●
Taiwan	●	UK	●	Ukraine	●	United States	●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present, the United States appears to be the leader.

The following organizations have active research programs:

- ***United States***
  - EMI
  - Precision Navigation
  - Sonar and Magnetometer Company
  - ZONG
- ***Russia***
  - URALS State Technical University (Laboratory of Quantum Magnetometry)

DATA SHEET III-16.4. MAGNETOMETERS—FIBER OPTIC

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level < 0.8 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Low noise level. Magnetic contamination, normally used for stationary applications. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of magnetic sensors in the past decade.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Applications of fiber-optic magnetometer include covert detection capability, area surveillance, and nondestructive testing.

Relative to JCS Vision 2010, SQUID magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●	Brazil	●	Canada	●●●
China	●	Czech Republic	●	Finland	●	France	●
Germany	●●	Hungary	●	India	●●	Israel	●
Italy	●●●	Japan	●●●	Netherlands	●●	Poland	●
Romania	●	Russia	●●●●	Slovak Republic	●	South Africa	●●
South Korea	●●●	Spain	●	Sweden	●●●	Switzerland	●
Taiwan	●●	UK	●●●	Ukraine	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present the United States and Russia are leaders.

The following organizations have active research programs in this technology:

- ***Russia***
  - URALS State Technical University
    (Laboratory of Quantum Magnetometry)

DATA SHEET III-16.4. MAGNETOMETERS—FLUX GATE (VALVE)

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level < 0.05 nT rms/√Hz at frequencies < 1 Hz and 10^{-2} nT rms per √Hz at > 1 Hz. Continuing development.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Only development and production technology should be controlled to reduce proliferation. Magnetic contamination. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW warfare, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade. Magnetic sensing of direction appears to be of secondary use by the military. Flux valve technology has been regulated to the "not glamorous" category of "common" sensors like the clock (see Section 16.5). There is, however, a need to provide low-cost map referencing of magnetic north and to maintain magnetic databases using magnetic sensors. A serious lack of knowledge exists relative to geolocation because of the increasing use of GPS as a sole means of navigation and position referencing. GPS does not provide direction unless a significant change of position is detected and north is then computed from the position differences. Magnetic heading referencing by the use of flux valve is the least costly means of solving this problem. Magnetic heading can be sensed by a flux value, for instance, or computed by subtracting a known magnetic variation from the true heading sensed by an INS. All aircraft, ships, and many land vehicles require magnetic heading (north) detection. A multichannel tensor gradiometer has been developed using fluxgate technology for tracking and homing applications in which less sensitivity is acceptable, but cost, size, weight, and logistics are important factors compared to SQUID and total-field sensing technologies. Flux gate gradiometers are especially useful to provide precise localization in man-portable operations.

Relative to JCS Vision 2010, flux gate (valve) magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●●	Brazil	●	Canada	●●●●
China	●	Czech Republic	●	Finland	●●	France	●●
Germany	●●	Hungary	●●	Israel	●●	Japan	●●
Netherlands	●	Poland	●●	Russia	●●●	South Africa	●●
Sweden	●●	Switzerland	●●	UK	●●●	Ukraine	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present the United States and Canada are the leaders.

The following organizations have active research programs:

- ***United States***
  - Applied Physics
  - Billingsley
  - EMD
  - GEM Systems
  - Nanotesla
  - Quantum Magnetics
  - Schoenstedt
  - Walker Scientific
- ***Russia***
  - URALS State Technical University (Laboratory of Quantum Magnetometry)
- ***Canada***
  - Narod
- ***UK***
  - Bartington
- ***South Africa***
  - Hermanus Magnetics Observatory

DATA SHEET III-16.4. MAGNETIC GRADIOMETERS USING MULTIPLE MAGNETOMETERS

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level of individual magnetometers of < 0.05 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Low noise level. Magnetic contamination. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Magnetic sensor systems are often configured to detect the spatial variation of the magnetic field intensity from sources external to the instrument, that is, the gradient of the magnetic field intensity, and in this mode are called magnetic gradiometers. Magnetic gradiometers can consist of two magnetic sensors or consist of a single intrinsic magnetic gradient sensor. Cost, application, and sensor capability dictate the choice. Magnetic gradiometers are key elements of magnetic anomaly detectors and are used in ASW, mine hunting, geology, area surveillance, and threat classification. They have covert detection capability.

Relative to JCS Vision 2010, magnetic gradiometers using multiple magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Canada	●●●●	China	●
Finland	●●	France	●●	Germany	●●	Hungary	●●
Israel	●●	Italy	●	Japan	●●	Netherlands	●
Poland	●	Russia	●●●●	South Africa	●	Sweden	●
Switzerland	●	UK	●●	Ukraine	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetic gradiometer technologies, while others are passive because of economic considerations. At present, the United States, Russia, and Canada appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - BTI
  - Quantum Magnetics
- ***Russia***
  - URALS State Technical University (Laboratory of Quantum Magnetometry)
- ***Canada***
  - CTF

BTI and CTF are advancing this technology using SQUID sensors, while Quantum Magnetics is using flux gate sensors.

DATA SHEET III-16.4. INTRINSIC MAGNETIC GRADIOMETERS

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level of < 0.015 nT/meter rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Low noise level. Magnetic contamination. Commercial equipment suitable for military applications.
Major Commercial Applications	Resource exploration.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for antisubmarine warfare, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Magnetic sensor systems are often configured to detect the spatial variation of the magnetic field intensity from sources external to the instrument, that is, the gradient of the magnetic field intensity, and in this mode are called magnetic gradiometers. Magnetic gradiometers can consist of two magnetic sensors or consist of a single intrinsic magnetic gradient sensor. Intrinsic magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminate the natural geomagnetic background noise. They are key elements of magnetic anomaly detectors and are used in ASW, mine hunting, geology area surveillance, and threat classification. Like all magnetic sensors, magnetic gradiometers have covert detection capability.

Relative to JCS Vision 2010, intrinsic magnetic gradiometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Brazil	●	Canada	●●●
China	●	Denmark	●	Finland	●●●	France	●●●
Germany	●●●	Hungary	●	India	●●	Israel	●●●
Italy	●●	Japan	●●●	Netherlands	●●	Poland	●
Romania	●	Russia	●●●	Slovak Republic	●	South Africa	●●
South Korea	●●	Spain	●●	Sweden	●	Switzerland	●●
Taiwan	●	UK	●●●	Ukraine	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetic gradiometer technologies, while others are passive because of economic considerations. At present, the United States appears to be the worldwide leader.

The following organizations have active research programs:

- ***United States***
  - Geophysical Institute (University of Alaska)
- ***Germany***
  - Julicher SQUID GmbH
- ***Denmark***
  - NKT

DATA SHEET III-16.4. MAGNETORESISTIVE MAGNETOMETERS

Developing Critical Technology Parameter	In next 5 to 10 years: Noise level < 0.03 nT rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms and/or using arrays.
Technical Issues	Low noise level. Magnetic contamination. Commercial equipment suitable for military applications.
Major Commercial Applications	Security applications.
Affordability	Not an issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Thin-film giant magnetoresistive (GMR) sensor technology appears at the present to provide a most promising possibility. On the one hand, the sensitivity of these sensors will likely increase and applications involving multiple units of low-cost, short-range, remote sensors will evolve. As sensitivity (high SNR) and compensation techniques improve, a wide variety of applications should evolve, such as covert detection capability, area surveillance, threat classification, and nondestructive testing.

Thin-film GMR sensor technology appears at the present to provide a most promising possibility (see Figure 16.4-2). Using GMR technology, nonvolatile random access memory will have lower power consumption and faster access speeds. GMR circuits, transformers, and logic gates are also viable. On the one hand, the sensitivity of these sensors will likely increase and applications involving multiple units of low-cost, short-range, remote sensors will evolve. Active electromagnetic detection of a target illuminated by a low-frequency magnetic or electrical-current source, currently utilized for land-mine detection, will likely be utilized in a wider range of applications as underlying sensor technology and signal-processing capabilities improve. Further advances in microelectronics, most significantly in the area of high dynamic range, multichannel, analog-to-digital converter technology and digital signal processing, will enhance capabilities and significantly reduce cost and complexity of the underlying sensor technologies. These factors will make concepts involving multiple units of low-cost, short-range, distributed sensors more attractive. Similarly, advancements in microelectronics will increase magnetic-sensor capabilities on magnetically noisy platforms through large-scale use of distributed sensors monitoring the platform noise.

Relative to JCS Vision 2010, magneto-resistive magnetometers have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●●	Brazil	●	Canada	●●●
China	●●●	Czech Republic	●	Finland	●●	France	●●●
Germany	●●●	Hungary	●	India	●●	Israel	●●
Italy	●●	Japan	●●●	Netherlands	●	Poland	●
Romania	●	Russia	●●●	Slovak Republic	●	South Africa	●
South Korea	●●	Spain	●●	Sweden	●●	Switzerland	●●
Taiwan	●●	UK	●●●	Ukraine	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetometer technologies, while others are passive because of economic considerations. At present, the United States appears to be the worldwide leader.

The following organizations have active research programs:

- ***United States***
  - Honeywell
  - Nonvolatile Electronics

DATA SHEET III-16.4. NONMAGNETIC CLOSED-LOOP REFRIGERATION EQUIPMENT

Developing Critical Technology Parameter	In next 5 to 10 years: Operation < 103 deg K. Continuing development.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	None.
Technical Issues	Nonmagnetic cooling environment allows for greater SNR for SQUIDs.
Major Commercial Applications	Resource exploration and medical applications.
Affordability	Medical imaging is funding driver.

RATIONALE

SQUID sensors are optimal (most accurate) when the cryogenic support equipment does not induce magnetic noise into the detection process. In the past, medical applications have been the only funded efforts in nonmagnetic closed-loop refrigeration equipment. With the advent during the last decade of high T_c SQUIDs, with critical transition temperatures in excess of 90 K, there has been intensified interest in closed-loop refrigeration for nondestructive evaluation and medical application. The cooling requirements are less stringent than what is required for low T_c technology.

Relative to JCS Vision 2010, nonmagnetic closed-loop refrigeration equipment has precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Brazil	●	Canada	●
China	●	Czech Republic	●	Finland	●	France	●
Germany	●	Hungary	●	India	●	Israel	●
Italy	●	Japan	●	Netherlands	●	Poland	●
Romania	●	Russia	●	Slovak Republic	●	South Africa	●
South Korea	●	Spain	●	Sweden	●	Switzerland	●
Taiwan	●	UK	●	Ukraine	●	United States	●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A few countries like the United States, Canada, Russia, and France have elected to be dominant in the associated technologies of SQUIDs that require superconducting operating temperatures. Other countries are passive because of economic considerations.

The following organizations have active research programs:

- ***United States***
  - ADP Cryogenics
  - GWR Instruments (Ultra Long Holdtime Dewar)
  - Neocera

DATA SHEET III-16.4. MAGNETIC ARRAYS

Developing Critical Technology Parameter	In next 5 to 10 years: Decrease of acquisition time and increase of accuracy of detection and location, array spacing, and detection range will increase with improved timing and communication.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement > 10 to 1) for operation on mobile platforms.
Technical Issues	Arrays provide greater SNR due to synergism of the sensors. Magnetic contamination can be isolated. Commercial equipment suitable for military applications.
Major Commercial Applications	Intrusion and security control.
Affordability	Not an issue. Availability and use of accurate time is the issue.

RATIONALE

In general, magnetometers and magnetic gradiometers are key elements of magnetic anomaly detector systems for ASW, mine fuses, intrusion and ordnance detection, proximity detection (distance to target), underwater mine detection, and active degaussing systems. There has not been significant progress in advancing the state of the art of many types of magnetic sensors in the past decade.

Magnetometers on a moving base are a POSITIME-influenced technology because of the interrelationship of magnetic data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The major advances in magnetometry during the last decade or so have been the emergence of precise location and time information and the availability of greatly enhanced computation capabilities. As these capabilities are introduced into magnetometry systems, the effectiveness of such systems could be significantly enhanced. Arrays allow for greater SNR of the system and reduction of SNR of the individual sensors in the array using compensation/synergism techniques. When a fixed array of sensors is used on the ground or underwater, the increased knowledge of position and time are coupled to enhance the computation power. The spectral energy density functions for environmental noise can be precisely deduced. Then, in the presence of a signal of interest, the special density function of the magnetic signatures of interest can be extracted from background noise and thus provide an SNR improved over that realizable without the use of energy spectral density techniques.

Applications include classification of objects not normal (intruders) to the environment, area surveillance, threat classification, and choke point control under covert conditions. Other applications include ASW, mine hunting, geology, and medical applications. The use of magnetometer arrays may be adapted by commercial users, but the main initial application will be militarily driven. The main differences between military and commercial use are the real-time accuracy requirements for operation from a moving base and the detection and classification capability.

Relative to JCS Vision 2010, magnetic arrays have precision engagement applications. There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	Russia	●	United States	●

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

Military and commercial interests are advancing the development and production of this technology. A few countries have elected to be dominant in magnetic array technologies, while others are passive because of economic considerations. Although the United States leads in platform motion compensation, Russia appears to have the lead in the use of compensation using magnetic sensor arrays.

SECTION 16.5—PRECISE TIME AND FREQUENCY (PT&F)

Highlights

- The worldwide availability of accurate time via GNSS will increase the combination of communications, imaging, and navigation functions into multihybrid sensor systems. This will provide a common grid reference for battlespace data management. The accuracy of the ionosphere model is a limiting factor on GPS time transfer.
- Autonomous and common three-dimensional POSITIME grid reference will improve battlespace situational awareness by providing a precise POSITIME tag on all battlespace information collected. This will provide real-time knowledge of the location and movement across battlespace of allied and enemy assets.
- Accurate time is required for autonomous operation of satellite network geolocation systems and enhanced crypto/transec performance in spread-spectrum communication systems.
- The importance of PT&F has only recently been recognized in military and commercial usage because of the availability of GNSS time. Foreign sources are currently providing the funding engine for future technology improvements in PT&F, as U.S. R&D funding has declined.
- The number of U.S. Atomic Frequency Standard suppliers is declining and may be down to one within 5 years.

OVERVIEW

PT&F is the key to current and future POSITIME, navigation, communication, and imaging systems. While the need of imaging and communication systems for PT&F is becoming more critical for military use, most current emphasis for PT&F technology is to support navigation and mainly for commercial use. Both the U.S. GPS, with its inherent vulnerabilities (see Section 16.3), and Russia's GLONASS worldwide navigation systems are actually PT&F systems. Both systems employ atomic clocks in the satellites. A cesium beam frequency standard is utilized aboard each GLONASS satellite. Both systems are capable of time transfer to a precision of 10 to 30 nanoseconds, but the GLONASS system time reference is not coordinated universal time, (UTC), as maintained at the United States Naval Observatory (USNO), the designated time reference for the United States. GPS uses both cesium and rubidium frequency standards in the current satellites, known as Block II/IIA, and rubidium standards in the replacement satellites, Block IIR. PT&F and signal detection and processing technology are required to acquire, synchronize, and track the desired satellite signals for measurement of navigation parameters. Technologies contributing to superior performance include the application of analog and digital correlation filters, DSP and microelectronics. Increased computational effectiveness for a given equipment volume and weight could provide an adversary with two distinct navigation payoffs: (1) certain navigation capabilities could be enhanced by advance computer technologies, and (2) for a given available volume/weight, the navigation performance could be enhanced in terms of accuracy, reliability, and resistance to hostile actions.

The GPS capability to transmit corrections to UTC (USNO) in the navigation message and thereby transfer time is given in the GPS Interface Control Document, ICD-GPS-202, as 28 nanoseconds (1 sigma). The 1997 Master Navigation Positioning and Timing Plan, CJCSI 6130.01A, requires timing accuracy to be 100 nanoseconds or better for all DoD users worldwide. The plan further states that precise time will be valuable to users who must time-synchronize other systems such as JTIDS (see Sections 16.1 and 16.3). The disparity between the documents exists because ICD-GPS-202 was recently updated to reflect increased user requirements. These wide-sweeping capability figures can still be misleading. The capability and conditions of time transfer from GPS depend greatly upon the instrumentation used, user conditions, and period of interest. For example, the time transfer capability of a fixed site, at a well-known position, needing long-term timing, and having the ability to integrate or process data over hours or days is considerably different than for a high-performance aircraft needing time to transfer in real-time or from the individual sensors of an array to a central processor. Time-transfer operational performance of GPS and data quoted is to a fixed site. GPS capabilities for military users under different conditions should be given as a more representative capability for system planning. Transfer of this technology will assist an adversary in improving the combat capability of its platforms. The use of stable clocks in a high dynamics platform can significantly improve timing availability by providing smoothing or "flywheeling" action that preserves time synchronization made under less stressed conditions.

Systems-integration technology enables the integration of communication and multiple navigational instruments outputs through advanced digital processing to provide an extended range of operational functions and increased combat performance. These technologies support reduced size and weight of equipment, improvement in navigation accuracy, continuity of operations, reliability, survivability, and resistance to enemy countermeasures. The substantial margin of capability added is critical to continued U.S. superiority in precision radio navigation and the multitude of missions dependent thereupon.

BACKGROUND

The importance of PT&F may be clearer with a description of the overall architecture of systems involved with the generation, dissemination, and maintenance of military common time. The overall process is described below.

- **Reference Time.** The common time scale to be used by U.S. military forces and systems is that generated, coordinated internationally, and maintained by the USNO. This time scale is designated internationally as UTC (USNO), representing the actual time available as a physical signal output of the USNO master clock. USNO maintains a master clock system of various commercial atomic clocks, remote precise time reference stations, and interface to dissemination systems. The alternate master clock became operational at Schriever Air Force Base in 1996 and is collocated with the GPS master control station as DoD's primary means of global time dissemination. The alternate master clock provides system redundancy and is linked to the master clock by a two-way satellite time transfer system. A severe handicap to users of UTC time, such as in telecommunications, is the yearly insertion of a nanosecond to account for the rotational changes of the Earth due to increases in the moon's orbital path around the Earth. In the next 5 to 20 years this correction problem needs to be internationally adjudicated to resolve the communication synchronization problem.
- **Reference Time Dissemination.** The dissemination of UTC (USNO) is accomplished by a collection of methods relying upon various systems, predominately POS/NAV systems. This dissemination function is a secondary mission of these systems, and no operational systems exist that are specifically designed and used for PT&F dissemination. Dependence upon secondary mission requirements or capabilities does not support a cohesive system architecture for the many systems that rely on precise time. Since PT&F is a secondary mission, operational control, coordination, and regulation of the time disseminated is an informal agreement without the impact of operational requirements. There are limited efforts underway to provide U.S. forces an affordable, nonjammable, precise, and accurate common time reference for all military electronic systems.
- **User Interfacing.** User systems have an increasing role in the distribution and sharing of time information. The Mark XV identification friend or foe (IFF) system and its counterpart North Atlantic Treaty Organization (NATO) identification system had a major problem in the distribution and synchronization of secure communications between their user platforms, which led in major part to the cancellation of the U.S. project. This should be a clear indication that the sharing of time information by user platforms and systems will be increasingly more important as higher data rates and crypto requirements (see Section 10) become more stringent. In turn, this will create an increasingly larger problem of controlling or managing intersystem timing exchange or interoperability. Coordination and standardization of these interfaces is part of the overall coordination role needed to produce robust systems synchronized to a common time reference.

RATIONALE

The importance of PT&F to military systems as a technology area is becoming more evident with the deployment and operational use of GPS. GPS provides the means for accurate and stable time to be disseminated to forces around the world. The application of GPS for timing is increasing, particularly in telecommunications and data transfer. As a result, the technology to maintain and use precise time is becoming of increasing military importance. However, because of the small quantity of Atomic Frequency Standard clocks that are needed yearly, the number of U.S. sources may decline to one within 5 years. Also alarming is the potential demise of the precision crystal oscillator suppliers in the United States in the near term. The oscillators are a critical module of the atomic clock system. There is a need for a precise, robust protocol for setting time across networks. A robust precision network time protocol (PNTP) using broadband communication links is needed for future military systems. The following table is an example of the possible types of needs that should be recognized for PT&F.

Table 16.5-1. User Clock Precision/Accuracy Requirements and Benefits

Platform/System	Current Accuracy to UTC (USNO)	Future Accuracy to UTC (USNO)	Benefit of Improved Time Accuracy
Nominal Use			
Time Epoch (second)			
Low-Accuracy Aircraft/Land Mobile	10^{-3}	10^{-9}	Quicker network entry for comms/IFF, enhanced crypto. Improved interoperability.
Ship/Submarines	10^{-6}	10^{-9}	Quicker network entry for comms/IFF, enhanced crypto. Improved interoperability.
Communication Sites/Aircraft	10^{-6}	10^{-9}	Quicker network entry for comms/IFF, enhanced crypto. Improved interoperability.
Radar/Surveillance/Intelligence	10^{-6}	10^{-9}	Better targeting/emitter location such as TDOA. Enable spread spectrum LPI.
Frequency ($\Delta f/f$)			
Low-Accuracy Aircraft/Land Mobile	10^{-12}	10^{-15}	Quicker network entry for comms/IFF. Improved interoperability.
Intermediate Land Reference Sites	10^{-13}	10^{-15}	Comms net access. Frequency calibration source for low-power oscillators.
Long-term Autonomous Timekeeping	10^{-13}	10^{-15}	Extended autonomous periods.
Large TDMA Systems	$\sim 10^{-11}$	10^{-15}	Enhanced network synch. Higher data rates.
Precise Mode (Cesium Calibration Updating)			
Time Epoch (second)			
ECCM Comm, Radar and Surveillance Systems	10^{-9}	10^{-11}	Better targeting/emitter location such as TDOA. Enable spread-spectrum LPI.
Submarine Comm, Ship	10^{-8}	10^{-11}	Enhanced network synch. Higher data rates. Longer autonomy. Enhanced navigation.

Current military fielded systems predominantly use cesium beam standards. These well performing and reliable devices have become the workhorse of remote timekeeping systems; however, they are large units not easily incorporated into smaller mobile platforms. Many users are therefore adopting secondary clocks, such as rubidium, disciplined by GPS time for long-term performance. These GPS-dependent clocks provide good performance in both long and short time frames, and the timing signals are being incorporated into many commercial systems such as telecommunication and computer networking systems. This dependency on a GPS-disciplined clock is a military concern. The following discusses the PT&F developing technologies that are being investigated for future PT&F requirements.

1. **Time Distribution.** More accurate and stable time sources, time distribution, and time transfer methods are required by the military to provide the warfighter with a coherent tactical picture and enable rapid, accurate capability assessment. With the closer logical linkage of combat systems and C2 systems and the proliferation of GPS units within precision weapons, the control of time sources and allowable variation of time provided by those sources to systems and elements across the battle space must be better managed. For example, better monitoring techniques could be utilized to improve time stability/accuracy performance by creating algorithms that combine clock outputs (ensembling) and automatically detect phase jumps or frequency perturbations and/or compensate for them. In addition, robust selection of alternative time source(s) in the event the preferred time source becomes unavailable must be better addressed. Present implementations often use multiple redundant clocks and GPS receivers and have no means of utilizing resources from other collocated systems. There is a strong need to establish a common time reference system, available across the platforms and battlespace, that will be usable by all systems. Such a system would include flywheel clocks at individual systems to provide autonomy from battle damage or loss of external references. Methods of time distribution other than GPS, particularly at the battlespace level, need development. These can include two-way satellite time transfer, fiber-optic systems for use within a platform, and other techniques such as communications systems between platforms.

2. **Atomic/Ion Clocks (Trapped Ion Storage and Slow Atom Technology Clocks).** This developing class of atomic clocks will improve absolute accuracy to better than 10^{-15}. Initially, these clocks will be larger, heavier, and more delicate than current military and commercial devices, but they have the potential to become competitive or better in size, weight, and power with existing clocks. This is a technology area where the Europeans are making great efforts and, in some cases, lead the United States.

   a. **Cesium Fountain Clocks.** Optical techniques for the containment and cooling of atoms, which was the 1997 Nobel Prize for Physics, offers new possibilities in methods for precise clock development. Optically contained neutral atoms can be cooled to close to absolute zero and launched into an interrogation system, which can make very accurate measurements of frequency to less than 1×10^{-15} sec/day. The immediate application being investigated is a "cesium fountain" clock. A clock of this type, theoretically proposed by Zacharis in the 1950's, is being developed by the National Institute of Standards and Technology (NIST) and USNO. The French have been operating such a clock at the Paris Observatory for several years, and NIST and the French are actively developing this technology for space application.

   b. **Mercury Linear Ion Trapped Clocks.** This type of magnetically trapped and optically interrogated clock is being developed by Jet Propulsion Laboratory (JPL) and is being deployed as replacement for the hydrogen master standards in the NASA Deep Space Network. One is to be tested for possible contribution to the master clock ensemble. These units employ mercury ions suspended in a magnetically generated linear trap and optically interrogated. These systems have the potential of extremely good stability for long-term measurements. HP did preliminary commercial product development on a mercury ion clock in the 1980's, but the design did not transition to production.

   c. **Other Technology Clocks.** Research into other types of trapped ion clocks and cooled cavity resonators is proceeding. The potential for migration into usable systems is estimated to be 5–10 years. These new, high-precision standards could contribute to the definition of reference time and time-scale generation, supporting a worldwide coordinated common time and potentially an improved time scale for DoD systems. The NIST microwave ion clock is pushing 10^{-15} second, and the optical version should realize 10^{-16} second when development efforts are funded to correct the optical frequency to the microwave region where it can be used in electronic systems. Large, research-oriented clocks could play a direct role in timing centers that are involved in the best performance clocks for time-scale operation. If successful in timing center improvements, this could again press the state of the art in dissemination and distribution of timing information to users.

3. **Low-Power Clocks.** There is a very strong need for clocks that perform at or near the accuracy level of current small clocks but at significantly reduced size, weight, and power. A technology currently in development, the microcomputer-compensated oscillator (MCXO), provides the stability of an ovenized crystal oscillator at or below the input power levels of the traditional temperature-compensated oscillator (TCXO). Another promising area of development is the miniaturized gas cell clock using cesium or rubidium. This approach trades off some performance of the traditional rubidium clock to provide an atomic clock with a volume of about 25 cm^3 and a power consumption of less than 1 W. These lower power devices can offer a level of performance suitable for GPS receiver direct-Y code acquisition and communications system synchronization in a package suitable in size and power for manpack or low-power mobile platform users.

4. **Optically Pumped Clocks**. The use of laser diodes for optical pumping and cooling of atomic systems to produce clock signals is a developing technology that will be adapted to field or system usable units. Low-power, fixed-mode diode lasers offer a natural means of interrogating and controlling small, ruggedized standards for field or platform use. French and Swiss companies have already introduced prototype small optically pumped cesium and rubidium units.

WORLDWIDE TECHNOLOGY ASSESSMENT

The United States has been the world leader in the development and utilization of PT&F technology for military electronic systems, including navigation, telecommunications, and data transfer. However, this leadership role is waning as U.S. R&D funds for PT&F technology have declined. The U.S. development efforts have been traditionally funded as parts of the host programs they support. As these programs, such as GPS, reached maturity, the funding for PT&F development vanished. NIST is operating a cesium fountain clock and is also developing this clock for space applications. Foreign PT&F developments are increasing, particularly in France, Switzerland, and in the European Space Agency (ESA) and associated research centers.

Country	Time Distribution Systems	Atomic Ion Clocks	Low-Power Clocks	Optically Pumped Clocks
Australia	●●●	●●	●●●	●●
Austria	●●	●	●●	●
Brazil	●●	●	●●	●
Canada	●●●	●●●	●●●	●●●
China	●●●	●●●	●●	●●
Czech Republic	●●	●	●●	●
Finland	●●	●	●●	●
France	●●●●	●●●●	●●●●	●●●●
Germany	●●●●	●●●●	●●●●	●●●●
Hungary	●●	●	●●	●
India	●●	●●	●●	●
Israel	●●●	●	●●●	●
Italy	●●	●●●	●●●	●●
Japan	●●●●	●●	●●●●	●●
Netherlands	●●	●	●●	●●
Poland	●●	●●	●●	●●
Romania	●●	●	●●	●
Russia	●●●●	●●●●	●●●●	●●●●
Slovak Republic	●●	●	●●	●
South Africa	●●●	●●	●●●	●●
South Korea	●●●	●●	●●●	●●
Spain	●●●	●●	●●	●●
Sweden	●●●	●●	●●	●●
Switzerland	●●●	●●●	●●●	●●
Taiwan	●●	●	●●	●
UK	●●●●	●●●	●●●●	●●●●
Ukraine	●●●	●●	●●●	●●
United States	●●●●	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.5-2. Precise Time and Frequency WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-16.5. PRECISE TIME AND FREQUENCY (PT&F)

DATA SHEET III-16.5. TIME DISTRIBUTION SYSTEMS

Developing Critical Technology Parameter	In next 5 to 10 years: Provide signal phase (time) common synchronization of < 10^{-9} sec, relative to UTC (USNO); intersystem synchronization of < 10^{-8} sec relative to battlegroup; coordinated use of platform resources for lower cost and robustness; 10^{-9} for interoperability, surveillance, and high-speed communication.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Frequency references for calibration with $\Delta f/f < 1 \times 10^{-15}$.
Unique Software	Algorithms and verified data to combine clock outputs to improve stability/accuracy performance (i.e., "ensembling"). Automatically detect phase jumps or frequency perturbations and/or improve reliability from redundancy. Self monitoring.
Technical Issues	Low noise, especially in the presence of vibration. Maintaining high stability under environmental extremes, e.g., the military temperature range. Survival and maintaining stability under high shock (gun-hardened oscillations). Accurate clocks are needed to provide direct wideband communication links and to provide direct acquisition of GPS-Y code. Flywheeling and other autonomous timekeeping techniques are essential. Power source may require further development for military application.
Major Commercial Applications	Telecommunication, electrical power generation, and grid management.
Affordability	Large volume use.

RATIONALE

The importance of this technology is becoming more evident with the deployment and operational use of GPS. GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer. As a result, the technology to maintain and use precise POSITIME is becoming of increasing military importance.

Sensors, such as magnetometers, magnetic gradiometers, gravity meters, gravity gradiometers, optical, infrared, ultraviolet, and acoustic, especially on a moving base, are POSITIME-influenced technologies because of the interrelationship of sensor data with position and time and the need for velocity and verticality compensation on a moving platform for sensor stabilization. The synergistic effect of the use of multiple sensor arrays is a major technology improvement that must be undertaken as a national policy on time.

More accurate and stable time sources, time distribution, and time-transfer methods are required by the military to provide the warfighter with a coherent tactical picture and enable rapid accurate capability assessment. With the closer logical linkage of combat systems and C2 systems and the proliferation of GPS units within precision weapons, the control of sources and allowable variation of time provided by those sources to systems and elements across the battle space must be better managed. For example, better monitoring techniques could be utilized to improve time stability/accuracy performance by creating algorithms that combine clock outputs (ensembling) and automatically detect phase jumps or frequency perturbations and/or compensate for them. In addition, robust selection of alternative time source(s) in the event the preferred time source becomes unavailable must be better addressed.

Present implementations often use multiple redundant clocks and GPS receivers and have no means of utilizing resources from other collocated systems. There is a strong need to establish a common time reference system, available across the platforms and battlespace that will be usable by all systems. Such a system would include flywheel clocks at individual systems to provide autonomy from battle damage or loss of external references. Methods of time distribution other than GPS, particularly at the battlespace level, need development. These can include two-way satellite time transfer, fiber-optic systems for use within a platform, and other techniques such as communications systems between platforms.

Joint Vision 2010 states that advances in computer processing, precise global positioning *(precise time)*, and telecommunications will provide the capability to determine accurate locations of friendly and enemy forces, as well as to collect, process, and distribute relevant data to thousands of locations *(timely)*. Joint Chief of Staff (JCS) positioning, navigating, and timing policy addresses the need for precise time and time-distribution systems. The Joint Science & Technology plans address the need for information *(precise time and time distribution systems)* superiority, including direct integration of GPS (precise time) with sensor outputs, distributed and collaborative virtual planning in real time, and integrated cross-sensor tracking with unique target ID and real-time updates.

Potential military applications of this technology include better synchronization, identification, surveillance, reconnaissance, remote sensing, and guidance. Improvements in time accuracy will (1) provide quicker network entry for communications, IFF, and enhanced crypto; (2) provide better targeting/emitter location, such as TDOA, and enable spread-spectrum LPI; and (3) enhance network synchronization and allow higher data rates.

There are no special requirements for the U.S. Government to gain access to this technology. There is a national need to take POSITIME more seriously in the United States. The substantial margin of capability added is critical to continued U.S. superiority in precision radio navigation, battlespace interoperability, and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●●	Brazil	●●●●	Canada	●●●
China	●●●	Czech Republic	●●	Finland	●●	France	●●●●
Germany	●●●●	Hungary	●●	India	●●	Israel	●●●
Italy	●●	Japan	●●●●	Netherlands	●●	Poland	●●
Romania	●●	Russia	●●●●	Slovak Republic	●●	South Africa	●●●
South Korea	●●●	Spain	●●●	Sweden	●●●	Switzerland	●●●
Taiwan	●●	UK	●●●●	Ukraine	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has been the world leader in the development and utilization of PT&F technology for military electronic systems, including navigation, telecommunications, and data transfer. However, this leadership role is waning as U.S. R&D funds for many PT&F technology have declined. The U.S. development efforts have been traditionally funded as parts of the host programs they support. As these programs, such as GPS, reached maturity, the funding for PT&F development vanished. Foreign PT&F developments are increasing, particularly in France, Switzerland, and in the ESA and associated research centers. The French have been operating with cesium fountain clocks at the Paris Observatory for several years and are actively developing one for space application. NASA is currently funding a space clock project to compete with the European effort, but this effort may be too small and too late. The NASA effort is a collaboration of NIST, University of Colorado, JPL, and Harvard Smithsonian.

The following organizations have active research programs:

- ***United States***
  - Absolute Time Corporation
  - Datachron Incorporated
- ***Switzerland***
  - MOBATIME
  - PRECITEL

DATA SHEET III-16.5. ATOMIC/ION CLOCKS

Developing Critical Technology Parameter	In next 5 to 10 years: Provide stability and accuracy approaching 1×10^{-15} sec for reference systems.
Critical Materials	Magnetic shields, low-noise local oscillators, and long-life stabilized lasers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Short-term performance may require new technology local oscillators for stability performance. Potential small size of high-performance and high-accuracy devices. Production sources of these low-volume units. Power source may require further development for military applications. Weight is critical. Low wattage, stable power required.
Major Commercial Applications	Telecommunication.
Affordability	High cost because of low-volume use.

RATIONALE

The importance of this technology is becoming more evident with the deployment and operational use of GPS. GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer. As a result, the technology to maintain and use precise time is becoming of increasing military importance.

This developing class of atomic clocks will improve absolute accuracy to better that 10^{-15} sec. Initially, these clocks will be larger, heavier, and more delicate than current military and commercial devices, but they have the potential to become competitive or better in size, weight, and power than existing clocks. This is a technology area where the Europeans are making great efforts and, in some cases, lead the United States.

Atomic clocks are composed of three general modules: a crystal oscillator, the atomic physics package, and the supporting electronics. Crystal oscillator availability from a U.S. source in the out years is of concern for Atomic Frequency Standard clocks. Crystal oscillators are key to the short-term stability and actual timekeeping because the atomic resonance frequency from the physics package is used to give long-term stability to the crystal clock. There are no issues relative to the physics package or the electronics.

Joint Vision 2010 states that advances in computer processing, precise global positioning *(precise time),* and telecommunications will provide the capability to determine accurate locations of friendly and enemy forces, as well as to collect, process, and distribute relevant data to thousands of locations *(timely).* JCS positioning, navigating, and timing policy addresses the need for precise time and time-distribution systems. The Joint Science & Technology plan identifies the need for information *(precise time and time distribution systems)* superiority, including direct integration of GPS (precise time) with sensor outputs, distributed and collaborative virtual planning in real time, and integrated cross-sensor tracking with unique target ID and real-time updates.

Potential military applications of this technology include better synchronization, identification, surveillance, reconnaissance, remote sensing, and guidance. Improvements in time accuracy will (1) provide quicker network entry for communications, IFF, and enhanced crypto; (2) provide better targeting/emitter location, such as TDOA, and enable spread-spectrum LPI; and (3) enhance network synchronization and allow higher data rates.

There are no special requirements for the U.S. Government to gain access to this technology. There is a national need to take POSITIME more seriously in the United States. The substantial margin of capability added is critical to continued U.S. superiority in precision radio navigation, battlespace interoperability, and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Brazil	●	Canada	●●●
China	●●●	Czech Republic	●	Finland	●	France	●●●●
Germany	●●●●	Hungary	●	India	●●	Israel	●
Italy	●●●	Japan	●●	Netherlands	●	Poland	●●
Romania	●	Russia	●●●●	Slovak Republic	●	South Africa	●●
South Korea	●●	Spain	●●	Sweden	●●	Switzerland	●●●
Taiwan	●	UK	●●●	Ukraine	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has been the world leader in the development and utilization of PT&F technology for military electronic systems, including navigation, telecommunications, and data transfer. However, this leadership role is waning as U.S. R&D funds for PT&F technology have declined. Another concern is the availability of crystal oscillators from U.S. sources in the 5- to 20-year period. The U.S. development efforts have been traditionally funded as parts of the host programs they support. As these programs, such as GPS, reached maturity, the funding for PT&F development vanished. Foreign PT&F developments are increasing, particularly in France, Switzerland, and in the ESA and associated research centers. For the last 5 years, the majority of symposia papers are non-U.S.

The following organizations have active research programs:

- ***United States***
  - Bliley Electric
  - Datum FTS
  - EG&G
  - Frequency Electronics, Inc.
  - HP
  - JPL
  - Kernco
  - NIST
  - Northrop Grumman
  - Piezo Crystal
  - University of Colorado at Boulder
- ***Australia***
  - National Measurement Laboratory
- ***Switzerland***
  - Oscillaquartz
  - Timex/Tekeler
  - Observatory at Neuchatel
- ***UK***
  - Quartzlock
- ***Japan***
  - Anritzu
  - Fujitzu
  - NEC

DATA SHEET III-16.5. LOW-POWER CLOCKS

Developing Critical Technology Parameter	In next 5 to 10 years: Provide accuracy and stability typical of current cesium and rubidium clocks at greatly reduced weight and power.
Critical Materials	Laser diodes, battery technology.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Achieving high accuracy in a small (1 cc) low-power (< mW) package. Accurate clocks are needed to provide direct wideband communication links and to provide direct acquisition of GPS Y code. Power source may require further development for military applications.
Major Commercial Applications	Telecommunication.
Affordability	Large volume potential.

RATIONALE

The importance of this technology is becoming more evident with the deployment and operational use of GPS. GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer. As a result, the technology to maintain and use precise time is becoming of increasing military importance.

There is a very strong need for clocks that perform at or near the accuracy level of current small clocks but at significantly reduced size, weight, and power. A technology currently in development, the MCXO provides the stability of an ovenized crystal oscillator at or below the input power levels of traditional TCXO. Another promising area of development is the miniaturized gas cell clock. This approach trades off some performance of the traditional rubidium clock to provide an atomic clock with a volume of about 25 cm^3 and a power consumption of less than 1 W. These lower power devices can offer a level of performance suitable for GPS direct-Y code acquisition and communications system synchronization in a package suitable in size and power for manpack or low-power mobile-platform users.

Joint Vision 2010 states that advances in computer processing, precise global positioning *(precise time)*, and telecommunications will provide the capability to determine accurate locations of friendly and enemy forces, as well as to collect, process, and distribute relevant data to thousands of locations *(timely)*. JCS positioning, navigating, and timing policy addresses the need for precise time and time-distribution systems. The Joint Science & Technology plan identifies the need for information *(precise time and time distribution systems)* superiority, including direct integration of GPS (precise time) with sensor outputs, distributed and collaborative virtual planning in real time, and integrated cross-sensor tracking with unique target ID and real-time updates.

Potential military applications of this technology include better synchronization, identification, surveillance, reconnaissance, remote sensing, and guidance. Improvements in time accuracy will (1) provide quicker network entry for communications, IFF, and enhanced crypto; (2) provide better targeting/emitter location, such as TDOA, and enable spread-spectrum LPI; and (3) enhance network synchronization and allow higher data rates.

Power availability is a weak link in the military. The need for standard, reliable power is one of the most serious problems in warfare. Accuracy is necessary for direct acquisition of GPS.

There are no special requirements for the U.S. Government to gain access to this technology. There is a national need to take POSITIME more seriously in the United States. The substantial margin of capability added is critical to continued U.S. superiority in precision radio navigation, battlespace interoperability, and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●●	Austria	●●	Brazil	●●	Canada	●●●
China	●●	Czech Republic	●●	Finland	●●	France	●●●●
Germany	●●●●	Hungary	●●	India	●●	Israel	●●●
Italy	●●●	Japan	●●●●	Netherlands	●●	Poland	●●
Romania	●●	Russia	●●●●	Slovak Republic	●●	South Africa	●●●
South Korea	●●●	Spain	●●	Sweden	●●	Switzerland	●●●
Taiwan	●●	UK	●●●●	Ukraine	●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has been the world leader in the development and utilization of PT&F technology for military electronic systems, including navigation, telecommunications, and data transfer. However, this leadership role is waning as U.S. R&D funds for PT&F technology have declined. The U.S. development efforts have been traditionally funded as parts of the host programs they support. As these programs, such as GPS, reached maturity, the funding for PT&F development vanished. Foreign PT&F developments are increasing, particularly in France, Switzerland, and in the ESA and associated research centers.

The following organizations have active research programs:

- ***United States***
  - Absolute Time
  - TrueTime Incorporated
  - Hewlett Packard
- ***UK***
  - Trimble Navigation, Ltd.

DATA SHEET III-16.5. OPTICALLY PUMPED CLOCKS

Developing Critical Technology Parameter	In next 5 to 10 years: Provide stability and accuracy approaching 1×10^{-16} sec for reference systems using smaller and lower power technology than ion clocks.
Critical Materials	Laser diodes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Developing stable, long-life laser diodes at the wavelengths required for optically pumped atomic clocks. Fills the gap between low-power technologies and ion clocks for field use. Power source may require further development for military applications. Ruggedized standards required.
Major Commercial Applications	Telecommunication.
Affordability	Beyond capabilities of most countries—low volume.

RATIONALE

The importance of this technology is becoming more evident with the deployment and operational use of GPS. GPS provides the means for accurate and stable time to be disseminated to forces around the world. The use of GPS for timing is increasing, particularly in telecommunications and data transfer. As a result, the technology to maintain and use precise time is becoming of increasing military importance.

The use of laser diodes for optical pumping and cooling of atomic systems to produce clock signals is a developing technology that will be adapted to field or system usable units. Low-power, fixed-mode diode lasers offer a natural means of interrogating and controlling small, ruggedized standards for field or platform use. French and Swiss companies have already introduced prototype small, optically pumped cesium and rubidium units.

Joint Vision 2010 states that advances in computer processing, precise global positioning *(precise time)*, and telecommunications will provide the capability to determine accurate locations of friendly and enemy forces, as well as to collect, process, and distribute relevant data to thousands of locations *(timely)*. JCS positioning, navigating, and timing policy addresses the need for precise time and time-distribution systems. The Joint Science & Technology plan identifies the need for precise time and time-distribution systems, information superiority, including direct integration of GPS (precise time) with sensor outputs, distributed and collaborative virtual planning in real time, and integrated cross-sensor tracking with unique target ID and real-time updates.

Potential military applications of this technology include better synchronization, identification, surveillance, reconnaissance, remote sensing, and guidance. Improvements in time accuracy will (1) provide quicker network entry for communications, IFF, and enhanced crypto; (2) provide better targeting/emitter location, such TDOA, and enable spread-spectrum LPI; and (3) enhance network synchronization and allow higher data rates.

There are no special requirements for the U.S. Government to gain access to this technology. There is a national need to take POSITIME more seriously in the United States. The substantial margin of capability added is critical to continued U.S. superiority in precision radio navigation, battlespace interoperability, and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Brazil	●	Canada	●●●
China	●●	Czech Republic	●	Finland	●	France	●●●●
Germany	●●●●	Hungary	●	India	●	Israel	●
Italy	●●	Japan	●●	Netherlands	●●	Poland	●●
Romania	●	Russia	●●●●	Slovak Republic	●	South Africa	●●
South Korea	●●	Spain	●●	Sweden	●●	Switzerland	●●
Taiwan	●	UK	●●●●	Ukraine	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The United States has been the world leader in the development and utilization of PT&F technology for military electronic systems, including navigation, telecommunications, and data transfer. However, this leadership role is waning as U.S. R&D funds for PT&F technology have declined. The U.S. development efforts have been traditionally funded as parts of the host programs they support. As these programs, such as GPS, reached maturity, the funding for PT&F development vanished. Foreign PT&F developments are increasing, particularly in France, Switzerland, and in the ESA and associated research centers. The French have been operating with cesium fountain clocks at the Paris Observatory for several years and are actively developing one for space application. NIST is also active in research in this area.

The following organizations have active research programs in this technology:

- ***France***
  - BNM Laboratories
- ***United States***
  - NIST

SECTION 16.6—SITUATIONAL AWARENESS/COMBAT IDENTIFICATION

Highlights

- RFID technology using secure, encrypted, millimeter waveform in the 33- to 40-GHz Ka-band will remain the primary NATO IFF capability to identify friendly forces in the battlespace for the foreseeable future. Advances in RFID technology will continue to improve performance, cost reduction, and size reduction.
- Advancements in long-range ATR databases, algorithms, and decision-aided tools, reducing the time needed to identify targets by a factor of three, will continue to complement RFID technology for positive identification of friendly, foe, and neutral targets.
- Increased usage of overhead intelligence, navigation, communication, and imaging sensor assets, using a common three-dimensional position and precise time grid reference, together with RFID/ATR systems, will provide reliable, positive, long-range identification capabilities within the lethality range of weapons.

OVERVIEW

At this time, this new section on SA/CID will only focus on the technologies that produce superior CID performance in the air-to-surface and surface-to-surface capability. Future updates of this document may address other SA/CID areas, including:

- Weather
- Air and ground traffic control
- Obstacle/ground/terrain avoidance
- Missile warning
- CID (air to air and surface to air).

SA includes all of the environmental, positional, and time conditions (past, present, and projected future) that affect the capabilities of the warfighter. Combat stress levels are inversely proportional to SA. Lack of SA will lead to adverse military decisions at all levels of command. CID plays a major role in achieving the capability to build and maintain a coherent tactical picture as discussed in the Section 16 overview and in Figure 16.6-1 below. CID is the capability to differentiate potential targets—mobile and fixed, over large areas with corresponding long distances—as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.[1]

The technologies include those needed for positive, timely, and reliable identification of friends, foes, and neutrals; classification of foes by class, type, and nationality; and interoperability required among the U.S. military and allied nations. The challenges are enormous, particularly in three specific areas: (1) a cooperative/noncooperative sensor systems; (2) a command, control, and communications (C3) systems—in particular, digital datalinks and radios, each of which contributes a portion to the CID solution; and (3) artificial intelligence tools that will fuse sensor and information, providing the warfighter with near-perfect, real-time discrimination between targets and non-targets on the battlefield. As such, CID is viewed as a capability, not a single system or technology. A "system-of-systems" approach is required. This subsection will consolidate the critical technologies addressed in the other MCT sections/subsections [Section 10 (Information Technology), Section 11 (Lasers and Optics), and Section 18 (Sensors)], as well as explore other technologies that will provide increasingly superior performance of SA/CID capabilities.

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1 *Joint Warfighting Science and Technology Plan: Combat Identification.*

This subsection will discuss three classes of technologies:

- *Sensors.* The target is characterized either noncooperatively (e.g., jet-engine modulation, high-range resolution radar, or electronic support measures) or cooperatively [e.g., MK XII (IFF) system or Battlefield Combat Identification System (BCIS)].
- *C3 (particularly digital datalinks and radios).* The target declares (either periodically or when queried) its identification and position in a reference frame that the "shooter" can correlate with its own weapon and sensor system (e.g., Link 16).
- *Artificial Intelligence Tools*. Vast amounts of data will need to be processed, correlated, stored, and displayed in real-time to be useful to a warfighter. AI tools include expert systems, intelligent agents, decision aides, modeling and simulation, and virtual reality.

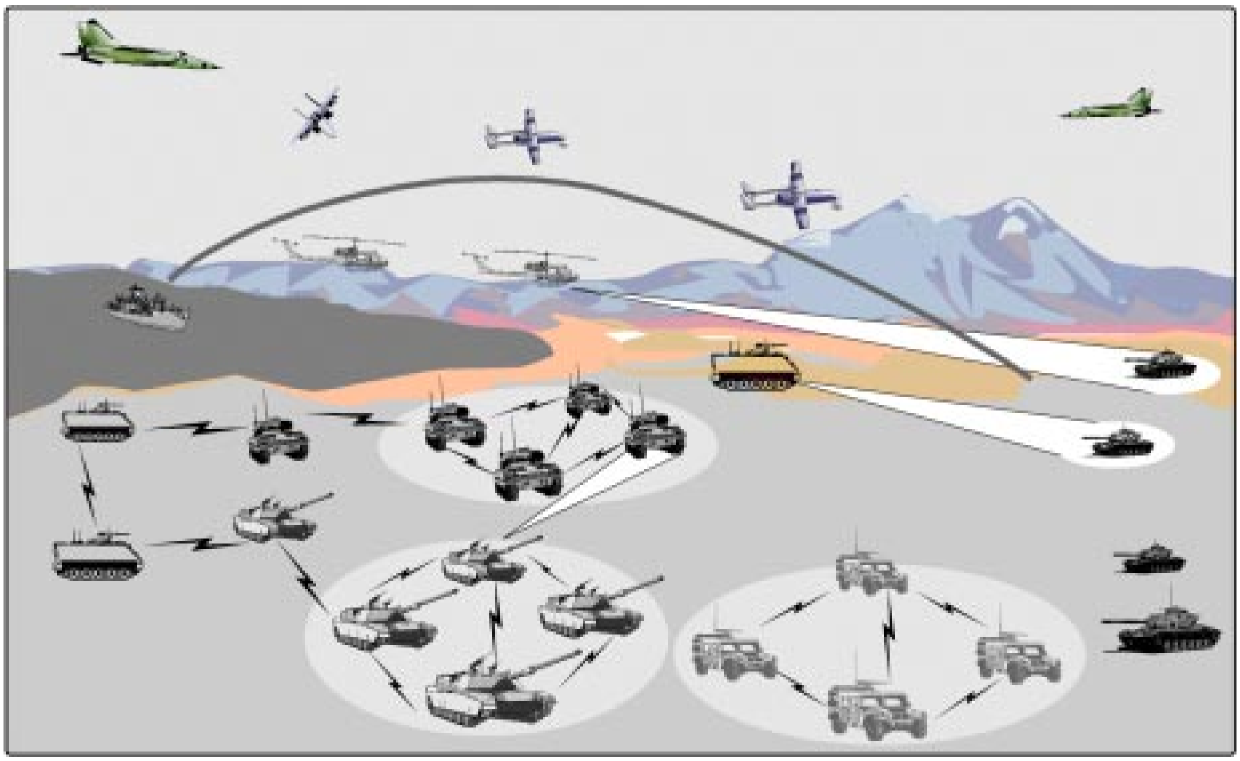

Figure 16.6-1. Concept Combat Identification

Currently, the cooperative tri-Service Mark XII RF/IFF system (circa 1970's) is the Q&A technology to identify friendly forces. Non-responses are considered unknown. Visual identification is used for neutral identification and foe identification in the air-to-surface and surface-to-surface areas, respectively. There is no long-range positive identification capability on the ground. As the lethality of weapon systems increases, and the speed and ferocity with which land battles are fought become greater, the need for systems that will aid warfighters in reducing fratricide are paramount. Making positive visual identification is difficult with allies and enemies using identical combat platforms and fighting battles under degraded natural and man-made conditions (obscurants, darkness, rain, dust, and fog). As proven in Operation Desert Storm, the confusion of a rapidly moving air-land battle using multinational forces creates a situational awareness nightmare.

Limitations in sensor resolution—coupled with variations in target aspect, state, countermeasures, and the battlespace signal propagation environment—complicate the job of target labeling. Improvements in sensors and target databases that expand the envelope of performance for these systems are necessary to increase target range, ID accuracy, and reliability.

Cooperative identification sensor systems, which only identify friends, have the advantage of being less of a technical challenge; however, they require all friendly potential targets to be equipped with the same corresponding identification equipment. This limitation will require more combined use of both cooperative and non-cooperative sensor systems.

Overhead CID technology sensor improvements that can interpret imaging and nonimaging sensor data to reliably identify the target ID in near real time are necessary. Communication improvements in secured data dissemination of SA multimedia information down to the lowest mobile echelon is required. The unprecedented amount of raw information produced by modern sensor systems and the effectiveness of C3 systems can overwhelm the capability of human operators and decision makers, requiring the need for a reliable automated decision aide tool. CID can be highly useful only when it is fully integrated with both C3 and weapon systems. CID requires effective and timely synchronization of communications systems with data from real-time surveillance, target tracking, and intelligence systems.

Affordability and exploitability are major barriers to having universal CID capability:

- **Affordability.** The cost of CID suites that are properly integrated with the weapon sight (both cooperative and noncooperative) are usually prohibitive if they are not form, fit, function and interchangeable (F3I) with an existing sensor or system. Additional functionality in the form of communications, SA, or sensing is helpful in making CID more affordable. The affordability of a system will also vary significantly depending on the environment in which it is considered. Aviation/maritime systems are generally more expensive than ground–based systems. As a result, solutions that are programmatically "affordable" for aircraft/maritime platforms are often prohibitively expensive for combat vehicles.

If the identification is determined by an off-board sensor, there is the added necessity to pass, correlate, and provide the warfighter the required information in a timely fashion. This requirement to correlate an identification label with a sensor return in the "weapon sight" is a key discriminator and a source of significant cost for the systems. Technology that eases the integration overhead of a CID-related system or reduces its component cost is required.

- **Signature Exploitability.** Noncooperative techniques of identification are most attractive to warfighters because of their ability to generate labels for foe, friend, and neutral contacts and because they can provide additional identification information on adversaries (e.g., platform type, class, nationality). For air/ maritime targets, the current capabilities of these systems are limited in range, aspect, and timeliness of reporting. The result is that the indications from this class of systems are frequently in the "unknown" or "not available" state. Improvements in sensors and target databases that expand the envelope of performance for these systems are necessary. For combat vehicles, the signal environment is such that reliable identification at maximum weapon range remains a significant technical challenge. Limitations in sensor resolution—coupled with variations in target aspect, state, countermeasures, and the battlespace signal propagation environment—complicate the job of target labeling.

Other issues are reliability and security. Unless the system is 100-percent reliable, possibilities exist for fratricide in combat. Antennas and other external devices (the BCIS uses an externally mounted transponder) may be blown off during combat, rendering the system useless. Another problem is security. If an enemy can read, jam, or duplicate the incoming or outgoing signals, the system's effectiveness becomes severely degraded. If the signals are not of an LPI nature, an enemy is likely to be able to localize emission sources and target them. It is also reasonable to expect that some of our systems will fall into enemy hands; therefore, our system must be reprogrammable. A different type of active system does not require interrogations but periodically transmits required information such as identity and status in the blind. This information "strobing" would have to be spectrally unique to prevent detection, but could simplify the overall system and allow one-half of the ID equation to remain passive. RFID tagging technology has great potential. This bar code system with a brain and voice can provide security in "secure" areas when the RFID tag is attached to the warfighter.

In the next 3–5 years, RFID technology using secure, encrypted, millimeter waveform in the 33- to 40-GHz Ka-band will remain the primary NATO IFF capability to identify friendly forces in the battlespace for the foreseeable future. Advances in RFID technology will continue to improve performance, cost reduction, and size reduction. Figure 16.6-2 shows the architecture interface concept for future U.S. Army combat identification systems to improve air-to-surface and surface-to-surface capabilities.

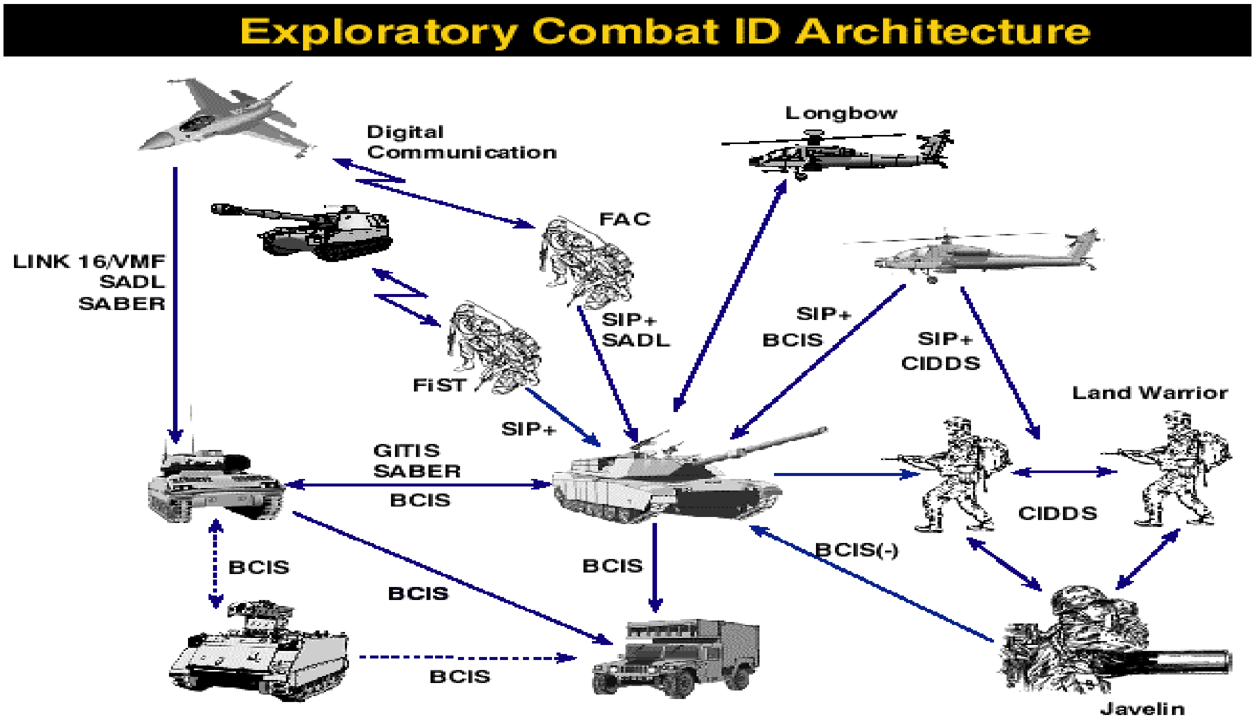

Figure 16.6-2. U.S. Army's Combat Identification Concept

- **For surface to surface.** Improvements in millimeter-wave technology, such as the U.S. BCIS, will provide identification of friends from unknowns at distances up to 14 km, day or night, with accuracy greater than 97 percent, reducing the risk of fratricide. BCIS allows the gunner or commander to make a rapid shoot/don't shoot decision at the point of engagement. Shooter platforms, e.g., tanks and fighting vehicles, are equipped with BCIS interrogator/transponder units that interrogate suspect platforms and respond to interrogations from other shooters. The interrogation process is automatically triggered by activation of the shooter's laser rangefinder, which sends an encrypted query to the targeted platform. If the target is friendly, its transponder receives the query and responds with an encrypted answer (nonshooter platforms are equipped with BCIS transponder-only units). When the interrogator receives an encrypted answer, it gives a "friend" response to the gunner/commander. If an invalid answer or no answer is received, an "unknown" response is provided to the gunner/commander, who then must continue using engagement tactics, techniques, and procedures. Responses are provided visually in the gunner's sight, as an audible tone on the intercom system, or both, eliminating the need for a gunner to remove his eyes from the target.
- **For air to surface.** The U.S. Army's single channel ground and airborne radio system (SINCGARS) improvement program [SIP(+)] is a "Don't Shoot Me System," consisting of a SINCGARS radio modified to use a GPS-coordinate-based message, enabling rotary-wing aircraft to interrogate ground-combat platforms equipped with SIP(+) radios using a "Don't Shoot Me" net feature.

In operation, the airborne SIP(+) radio transmits the interrogation message, which includes the targeted position. If an interrogation is detected by the SIP(+) ground radio and the target coordinates match, it transmits a "Don't Shoot Me" response to the airborne interrogator. The total interrogation/response cycle should take a maximum of 2.3 sec. Future improvements may reduce this to less than 1 sec.

In the next 5–10 years, advances in ATR algorithms and systems will provide a passive capability to distinguish between targets and nontargets automatically and noncooperatively. Concurrent with significant advances in information systems (see Section 10), ATR algorithms will be used more and more as a complement to RFID systems (i.e., BCIS/SINCGARS + ATR). During this period, ATR algorithm development will achieve significant growth, particularly in integration with multisensors and new ATR techniques (i.e., matched filtering, pattern recognition, model based, and clutter and edge modeling).

- **For surface to surface.** The Land Warrior System, a first-generation integrated fighting system for dismounted combat soldiers, will enhance the soldier's battlefield capabilities through the development and integration of a variety of Army components and technologies into a cohesive, cost-effective system. The Land Warrior System includes a computer/radio subsystem, a GPS receiver, a magnetic compass, a dead-reckoning navigator, VHF and UHF radios, and a video capture capability. The Integrated Helmet Assembly Subsystem includes a heads-up display and image intensifier for night operations and a weapons subsystem with thermal weapon sight, close combat optics, video camera with a video capture capability, laser range-finder/digital compass, and an infrared laser aiming light. The system also includes protective clothing, load carrying equipment, body armor, a chemical/biological mask, and a laser detector. Improvements during this period could maximize the tactical CID performance with a view of the battlefield that exploits the time-critical combat information provided by an integrated SA and target identification (TI) system. Future potential capabilities are ATR and external near real-time (NRT) sensor cueing from overhead radar and satellites. To overcome the exploitable issues addressed and approach the 100-percent-reliable ID will require both active and passive technologies to be used. For active interrogation/responses should be multispectral; utilizing acoustics, IR, visual bands, RF, millimeter wave, and laser beams. It is also reasonable to expect that some systems will fall into enemy hands; therefore, the system must be reprogrammable.
- **For air to surface.** Improvements in communication systems (see Section 10), such as the Air National Guard's Situational Awareness Data Link Forward Air Controller (SADL FAC) system could provide information on friendly ground force positions as well as calculate the position location of laser targets. This system determines friendly ground force positions through use of the SADL (EPLRS) radio. The Mark VII Laser Rangefinder and the Precision Lightweight Global Positioning System Receiver (PLGR) generate the target location information. This information is digitally transmitted via the SADL radio to the SADL-equipped CAS aircraft. Another example is the U.S. Navy's Situational Awareness Beacon with Reply (SABER) program, which consists of a miniature UHF SATCOM transceiver and an integrated GPS receiver to provide a combined SA/direct-target ID solution for ground platform, fixed-, and rotary-wing aircraft performing air-to-ground missions. A beacon is installed on friendly ground platforms to enable them to periodically transmit an identification code, geolocation (position) information, and other host platform data either directly to line-of-sight receivers using ultrahigh frequency (UHF) radios or indirectly via an UHF satellite link using a low probability of intercept/low probability of detection (LPI/LPD) waveform called "Collection of Broadcasts from Remote Assets" (COBRA).

In the next 10–20 years, further improvements in information systems will provide a new class of high-data-rate, networked radio communications as part of command and control systems. These radios will have the ability to deliver data within specified time lines using prioritization and quality of service routing techniques. The combination of higher data rates, more reliable networking, and quality of service routing will enable these networks to provide significant, timely information on friendly situations, to include friendly locations and identifications. This information will contribute directly to Combat Identification. A particularly critical enabling set of technologies for these new high-data-rate radio communications systems will be low probability of intercept (LPI)/low probability of detection (LPD) waveforms. Wavelet overlay technology is particularly critical. Use of multisensors integrated with ATR algorithms and data bases and nanotechnology (providing more affordable position and precise time tagging) will also significantly increase SA/CID reliability and reduce target ID time to near real time. For example, the U.S. Air Force Spacecast 2020 study suggested an exotic space-based target recognition scheme in which a laser beam from a satellite would scan the battlefield, and the reflected energy would be analyzed by sensors on the spacecraft. By comparing the spectra, identification would be possible. Friendly tanks and aircraft could be chemically coated to produce a characteristic spectrum when excited by the space-based laser, proving a degree of IFF capability. Using techniques likened to "licking" and "tasting" to identify objects on the ground, the licking would be done by a laser beam fired from a satellite, which would be equipped with sensors that would "taste" the spectrum of the radiation reflected back from the target. By comparing this with a database of know tastes it would be possible to identify an object. Friendly tanks and aircraft could be coated with a chemical that produces a characteristic spectrum when excited by energy of a certain frequency or other characteristic.

- **For surface to surface.** The range and reliability at which identification can be reliably accomplished can be improved with increased use of overhead asset data and image technology and more use of smart RFID tagging. All weapons could include semi-passive interrogation systems that read the identity from a tag or label of some type, such as an RFID, on the vehicle or person. Integrated with a passive system, ATR pattern recognition could discriminate enemies from friendly and combatant from noncombatant. Using ATR and pattern recognition logic could assist in threat determination of noncombatants, based on discriminators such as vehicle type, color, and motion, or observations that personnel are carrying weapons, moving in a tactical manner, etc.
- **For air to surface.** A fully interoperable NATO C3 system (such as Link 16/22) could provide (1) friend identification automatically (for all friendly combat participants on the network); (2) a medium for passing hostile/neutral identification generated from other sensors/sources; and (3) a medium for passing friend identification (for those platforms not on the network) generated from other sensors/sources. Addressing the interoperability issue, the United States is migrating towards a J–series family of datalinks to include Link 16 for air operations, Link 22 for maritime operations, and variable message format (VMF) for ground operations. For air, maritime, and ground weapons, this could play a significant role in sorting friend from foe or neutral in the battlespace.

By 2025, friendly troops and equipment will enter the battlespace with their personal identifiers. The identification mechanisms could be in the form of microchips worn by or imbedded in the soldiers. The same principle could be applied to vehicles. An active or passive system could identify friendlies by reading a label attached to an object. As the battlenet sensors detect each target in the battlespace, they apply a physical label to the target. For example, a particle beam imprints coded information on the exterior of specially painted vehicles or irradiates the clothing of exposed personnel. Labels placed on targets could be magnetic, optical, or electronic, and can be sized down to the molecular level. The label contains data that includes the type of target, date time group, and military unit controlling the vehicle or person. Sensors would be required to interrogate an unknown transponder, analyze the response, and determine if the response came from a friendly system or a designated hostile system. If the interrogator receives a response that does not correspond to known friendly systems or fails to receive a response at all, the interrogator activates a separate series of identification methods involving discriminators such as material composition, acoustic, electromagnetic, thermal, or vibration signatures. For situations involving a mixture of hostile forces and noncombatants in an environment where no external evidence distinguishes the two (a riot or urban disturbance, for example), the system may need only distinguish between friendly “tagged” personnel and others.

RATIONALE

U.S. forces must be able to positively identify all targets in the battlespace for all combat mission areas—air to air, air to surface, surface to surface, and surface to air. Surface includes land, sea, and subsurface—otherwise known as ground and maritime. The CID need is essential for commanders to effectively field, at any time, fighting forces that can rapidly and positively identify enemies, friends, and neutrals in the battlespace; manage and control the battle area; optimally employ weapons and forces; and minimize the risk/occurrence of fratricide.[2]

Lack of positive target identification and the inability to maintain SA in combat environments are the major contributors to fratricide. Vehicle commanders, gunners, and attack pilots cannot distinguish friendly and enemy thermal and optical signatures at the ranges at which they can be acquired. Our weapons can kill beyond the ranges where we have clear ID. Our tactics lead us to exploit our range advantage over the enemy. During limited visibility or in restricted terrain, units in proximity can mistake each other for the enemy because of short engagement windows and decision time. We do not have a means to determine friend or foe, other than visual recognition of our forces and the enemy’s.

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[2] *Joint Warfighting Science and Technology Plan: Combat Identification.*

When the enemy and our allies are equipped similarly, and when the enemy uses U.S. equipment, the problem is compounded. Simple, effective fire and maneuver control measures and plans, good SA, and disciplined engagements are absolutely necessary. The long-range vision of CID is to enable U.S. forces to positively identify all targets in the battlespace for all combat mission areas. Our fighting forces must be able to rapidly and positively identify enemies, friends, and neutrals; manage and control the battlespace; optimally employ weapons and forces to increase economy of force; lower combat attrition and increase enemy losses; and minimize the risk and occurrence of fratricide. To achieve this will require significant improvements in these critical technologies: sensors, C3, and AI tools.

WORLDWIDE TECHNOLOGY ASSESSMENT

The development leaders of SA/CID technologies are for the most part located within the NATO countries. To coordinate national combat identification work, France, Germany, the UK, and the United States established a four-nation Combat Identification Working Group (CIWG) in October 1992. A final report in January 1998 recommended Ka-band (33–40 GHz) Q&A as the most cost and operationally effective technology for interoperable target identification for the long term (2001+). This was approved, and the four-nation CIWG is working to develop a standardization agreement (STANAG) for NATO target identification.

Under a program being jointly conducted by the U.S. Air Force's Wright Laboratory, the Massachusetts Institute of Technology/Lincoln Laboratory, Sandia National Laboratories, the U.S. Naval Air Warfare Center, the U.S. Army Research Laboratory, and 15 other university and industry organizations in the United States, signature-prediction codes are being developed. These codes will cope with frequencies ranging from B to K band and with targets consisting of electrically conducting material, homogeneous and isotropic frequency-dependent materials, radar-absorbing nets, and nonmetallic structures made from glass fibre and other semitransparent materials. The task of compiling the more than 10 million signatures and images required for noncooperative target recognition development and operational fielding will take several years, even with fast computers running around the clock.

Country	Sensors	C3	Artificial Intelligence
Australia	●●	●●●	●●
Austria	●●	●●●	●●
Belgium	●		
Canada	●●	●●●	●●
China	●●	●●	●
Finland	●		●
France	●●●●	●●●●	●●●●
Germany	●●●●	●●●●	●●●●
Israel	●●●	●●●	●●●
Italy	●●	●●●	●●●
Japan	●●	●●●	●●
Russia	●●●	●●●	●●
South Korea		●●	
Sweden	●		●●●
Switzerland			●●
UK	●●●●	●●●●	●●●
Ukraine	●●	●●	
United States	●●●●	●●●●	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 16.6-3. Situational Awareness/Combat Identification WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
III-16.6. SITUATIONAL AWARENESS AND COMBAT IDENTIFICATION

Note: For other related sensor technologies, see Sections 11 and 18. For other communication and information technologies, see Section 10.

DATA SHEET III-16.6. IDENTIFICATION FRIEND OR FOE, MILLIMETER-WAVE (mmW) TECHNOLOGY

Developing Critical Technology Parameter	In the next 3 to 5 years: Ground-to-ground identification ranges 5–25 km day or night, clear sky, rain, or dust. Air-to-ground identification ranges 100–200 miles. Identification time: < 1 second. Probability of correct ID 90%–97%.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	The Battlefield Identification System Environment and Performance Simulator (BISEPS) system has been developed in support of MMW/BCIS performance evaluation. BISEPS computes the probability of correct identification and measures net latency.
Unique Software	The various technologies that will reduce fratricide must be integrated into an overall architecture. Can be configured to send, receive, and display secure, digital information with other similarly equipped units on the battlefield.
Technical Issues	Requires friendly targets to respond to interrogation. Assumes non-responses as unknowns. Detectability/exploitability of signals.
Major Commercial Applications	Air traffic control, vehicle identification, railcar stacking, and location.
Affordability	Integration and interoperability are major cost drivers.

RATIONALE

This technology provides positive identification of friendly platforms and dismounted soldiers from both ground and air weapons platforms and dismounted soldiers. System includes interrogators and transponders combined for shooters and transponders only for nonshooters

Improvements in mmW technology, such as the U.S. BCIS, currently provide identification of friends from unknowns at distances up to 14 km, day or night, with accuracy greater than 97 percent, reducing the risk of fratricide. BCIS allows the gunner or commander to make a rapid shoot/don't shoot decision at the point of engagement. Shooter platforms (e.g., tanks and fighting vehicles) are equipped with BCIS interrogator/transponder units that interrogate suspect platforms and respond to interrogations from other shooters. The interrogation process is automatically triggered by activation of the shooter's laser range finder, which sends an encrypted query to the targeted platform. If the target is friendly, its transponder receives the query and responds with an encrypted answer (nonshooter platforms are equipped with BCIS transponder-only units). When the interrogator receives an encrypted answer, it gives a "friend" response to the gunner/commander. If an invalid answer or no answer is received, an "unknown" response is provided to the gunner/commander, who then must continue using engagement tactics, techniques, and procedures. Responses are provided visually in the gunner's sight, as an audible tone on the intercom system, or both, eliminating the need for a gunner to remove his eyes from the target.

This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at their longest lethal range. CID technology is a major element of the Joint Warfighting Science and Technology Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

An mmW Transponder for dismounted-soldier CID is under development by the U.S. Army. A prototype brassboard Ka-band transponder, which used a state-of-the-art high-stability dielectric resonator oscillator transmitter for interrogation, was developed and demonstrated. A low-noise receiver and initialization circuitry were designed, built, and used to demonstrate the feasibility of using mmW technology for CID. The mmW approach to soldier CID offers a highly portable device that can penetrate smoke, fog, dust, and rain and have a low probability of intercept and low probability of spoofing or jamming.

Continued research to integrate noncooperative technologies, such as ATR, and overhead surveillance/intelligence information, needs to be pursued to validate a Q&A system's nonresponder as foe. Reducing the time for the shooter to obtain a positive identification should also be a major objective of the research.

This Q&A technology will remain the primary means of NATO to identify friendly forces in a combat environment for the foreseeable future. However, future integration with other noncooperative and ATR technologies will enhance its capabilities to provide a positive identification, not only of friendly targets, but also foe and neutral targets.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Belgium	●	Canada	●●●
China	●	Finland	●	France	●●●●	Germany	●●●●
Greece	●	Israel	●●●	Italy	●●●	Japan	●
UK	●●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

MMW research for CID is being carried out primarily by NATO countries. At present, the United States, France, Germany, and the UK are the world leaders.

The following organizations have active research programs in this technology:

- ***United States***
  - Magnavox
  - TRW
  - Raytheon
- ***France***
  - ALCATEL
  - Thomson-CSF Communications
- ***Germany***
  - Daimler-Benz Aerospace AG
- ***UK***
  - British Aerospace Systems, Ltd.

DATA SHEET III-16.6. DATA FUSION/ARTIFICIAL INTELLIGENCE/ DECISION AIDS TECHNOLOGY

Developing Critical Technology Parameter	Fuses information from a wide variety of sources to bring the confidence factor of the target identity to near 100 percent.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms for tracking a large number of targets in a cluttered environment.
Technical Issues	To develop the capacity to reason in the face of uncertainty and to fuse information from disparate sources. Timely ability to combine, analyze, and integrate enormous volume and variety of data. Multisensor integration requires expanded network communication bandwidth.
Major Commercial Applications	Manufacturing quality control, internal medicine, financial market analysis, information retrieval. Multimedia medical database. Waste management.
Affordability	Integration and interoperability are major cost drivers.

RATIONALE

Complex problem solving in warfighting typically requires the problem solver to access and combine data from multiple sources and to develop a dynamic assessment of an evolving situation. Data fusion focuses on providing the distributed tools and systems infrastructure to fuse data from multiple network sources. These data are combined with other knowledge and planning tools to make and evaluate several alternative plans. This could improve the ability to detect new situations, develop and evaluate alternative plans, and respond quickly to new combat threats and opportunities.

Advanced information fusion will be expected to provide near-perfect, real-time discrimination between targets and nontargets on the battlefield. AI technologies will be key to solving the awareness/ knowledge problem. AI tools aid decision systems, intelligent agents, modeling, simulation, and forecasting. Vast amounts of digital data will need to be processed, correlated, stored, and displayed without swamping users. The data base of a particular battlespace will have to be continuously updated with real-time information to make it useful to a warfighter. Multisource integration and data fusion will reduce the shooter's workload/stress levels by providing relevant and accurate information of the tactical battlespace picture. Current methods of data fusion are

- Extended Kalman filtering
- Model-based approaches
- Wavelet decomposition
- Artificial neural networks
- Fuzzy logic.

The *Quadrennial Defense Review* identifies the key to future success for U.S. forces as being an integrated "system of systems," linking intelligence collection and assessment, C2, weapons systems, and support elements to achieve battlespace awareness. Achieving this will require vast amounts of data, necessitating automatic decision-making tools.

This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at their longest lethal range. The fusion of all-source intelligence with the fluid integration of sensors will allow a greater number of operational tasks to be accomplished faster.

CID technology is a major element of the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release. The Joint Warfighting S&T Plan's precision force identifies the use of multisensors, ATR, and sensor fusion as key technologies to provide a real-time, fused battlespace with integrated decision-aid tools. The Navy CID Working Group concluded that multisource integration and data fusion are required to meet CID requirements.

A data-fusion system for identifying and classifying active sonar contacts is being developed by the U.S. Navy. It analyzes various sources of data and fuses the response into a single opinion, answer, or decision.

Battle damage assessment (BDA) today is a haphazard, unlinked, slow process largely confined to BDA reports, spot reports, and other intel fragments; gun-camera footage; and CNN. A DARPA program uses models to determine what information is required to assess it, requests that information to be gathered, passes condition-of-interest requests to external situation monitors, reacts to new information by relating it to the requesting model agent, updates models, and produces assessments.[3]

Methods developed in the field of AI include the following:

- Common-sense reasoning
- Nonmonotonic logic
- Circumspection
- Algorithms used in neural networks
- Extensions to Bayesian calculi.

Most ATR development, being based on analysis of single image frames and segmented target regions, is currently limited to the pattern recognition subset of recognition theory. More generalized ATR processing would take advantage of multiple geo-registered information sources and temporally displace data in order to dynamically reason about situations. A future is feasible where sensors and information will be ubiquitous.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

Further research and development is needed to develop the capacity to reason in the face of uncertainty and to fuse information from disparate sources.[4]

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3 www.teknowledge.com

4 *Information in Warfare,* Chapter 3, www2.nas.edu/nsb2/iw3.htm

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Belgium	●●	Canada	●●●
China	●	Finland	●	France	●●●●	Germany	●●●●
Greece	●	Israel	●●●	Italy	●●●	Japan	●
Norway	●●	Russia	●●	Spain	●●	Sweden	●●
Switzerland	●●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Data fusion and artificial intelligence research is being carried out throughout the industrialized world. At present, the United States, France, and Germany appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - AlphaTech
  - Coleman Research Company
  - Naval Research Laboratory (Navy Center for Applied Research in AI)
  - Raytheon
  - Sona Lyst Incorporated
  - SRI
  - Sterling Software
- ***Norway***
  - Universitetet I Oslo
- ***France***
  - Alcatel
  - Laboratory SURFACES
  - Thompson-CSF
  - University of Paris
- ***Germany***
  - FGAN
  - Humbolt University
  - Technical University of Braunschweig
- ***UK***
  - British Aerospace
  - CNR
  - TWI
- ***Switzerland***
  - Dalle Molle Institute for Studies on AI
  - Swiss Centre for Scientific Computing
  - Swiss Federal Institute of Technology
- ***Netherlands***
  - Hollandse Signaal
- ***Denmark***
  - Aalborg University

DATA SHEET III-16.6. AUTOMATIC TARGET RECOGNITION (ATR) ALGORITHMS

Developing Critical Technology Parameter	In next 5 to10 years: Model-based or neural-network-based reasoning integrated with pattern recognition promises reliable target detection with low false alarms (0.01 false alarms/km^2).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms for tracking a large number of targets in a cluttered environment.
Technical Issues	ATR algorithms must cope with three-dimensional objects, the exact shape of which may be poorly known and which may appear at any orientation, under widely varying lighting and visibility. Decoys, camouflage, shadow, or darkness can deceive a shaped-based ATR system. Increasing capacity for dense memory storage, computer processing speeds, and high bandwidth for data transfer.
Major Commercial Applications	Tracking high-value vehicle and rail cargo. Robotics. Medical analysis.
Affordability	Integration of ATR and sensor data is a key affordability issue, which can reduce warfighter workload and stress levels.

RATIONALE

ATR algorithm technology provides a noncooperative, real-time capability beyond the visual range of target. This capability, when integrated with other cooperative identification systems, provides a very high probability of detection and identification of friend, foe, and neutral targets. The development of both data-driven and model-based approaches using single and multiple sensors are two means to achieve this capability.

ATR data-base development includes target signature modeling and scene synthesis efforts that support ATR algorithms for single/multisensor electro-optics and radar systems. Signature modeling is critical to rapid target identification. Synthetic data also provides a practical means of exploring complex, multi-sensor ATR designs. Scene syntheses provide high-fidelity models for distributed, interactive simulations to assess new ATR technologies.[5] A new method of edge detection and image enhancement overcomes many of the defects of past approaches by locating edges with subpixel resolution and limiting edge distortion.[6] Better clutter modeling techniques will improve detecting a tank or truck in a heavily cluttered environment, such as a battlefield.[7]

Joint Vision 2010 identifies ATR technology as a means to enhance the detectability of targets across the battlespace, improve detection ranges, turn night into day, and reduce the risk of fratricide. This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at its longest lethal range. CID technology is a major element of

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5 *1997 Defense Technology Area Plan,* "Sensors, Electronics, and Battlespace Environment."

6 "Digital Signal Processing," Seminar, The University of Texas at Austin.

7 www.cis.ohio-state.edu

the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

An application for ATR systems is the ability to detect targets passively for either direct attack or subsequent attack by conventional or guided weapons. It can also provide high-accuracy terminal guidance for "smart" missiles. If a gyro navigation system, GPS, or other systems can steer the missile to a precisely defined location, the task of the seeker and the complexity of its ATR algorithms will be significantly reduced. Another application involves a mathematical approach to target identification using a reconnaissance photo that is scanned directly into the ATR system. Matching the entire digitized scene to a real-time infrared image of the target area makes the ATR insensitive to landscape changes that can obscure targets, e.g., scene contrast, battle damage, smoke obscuration, seasonal changes, and thermal contrast.

In the future, ATR-type systems will be a significant addition to the NATO Q&A systems, and they will be in high demand for future warfighting, where the requirement is not only to reduce fratricide, but also to reduce collateral damage to civilians and civilian infrastructures. Currently, this technology is in its infancy, with no single ATR algorithm suitable for all combat situations and environments. For this reason ATR technology should be followed over time.

The following enhancements of this technology should be pursued:

- Larger mass storage devices, rapid retrieval, and faster computing processors, a leveraged technology for ATR systems (see Section 10)
- Expanded ATR model-based reasoning technology for multiple sensor sources of information
- Expanded hybrid ATR systems, including clutter modeling, scenario and behavioral models, integrated with sensor(s) for positive target detection and identification.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●	Belgium	●	Canada	●●●
China	●	Finland	●	France	●●●●	Germany	●●●
Greece	●	Israel	●●●	Italy	●●●	Japan	●
Norway	●●	Russia	●	Spain	●	Sweden	●●●●
Switzerland	●●	Taiwan	●●	UK	●●●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

ATR research is moving to a maturity level. Numerous universities worldwide have research programs in this technology. At the present time, the United States, the UK, Sweden, and France appear to be the leaders.

The following organizations have active research programs in this technology:

- ***United States***
  - Air Force Research Laboratory
  - Air Force Wright Laboratory
  - Boeing
  - Carnegie Mellon University
  - Center for Imaging Science (Washington University)
  - DARPA
  - HNC Software
  - Lockheed-Martin
  - Massachusetts Institute of Technology
  - Naval Surface Warfare Center, ID Vision
  - Navy Research Laboratory
  - Photon Research Associates
  - Raytheon
  - SRI
  - University of Missouri
- ***UK***
  - British Aerospace
  - Defense Evaluation Research Agency
  - GEC-Marconi
  - Matra BAe Dynamics
- ***France***
  - Sagem
- ***Sweden***
  - Ericsson Saab Avionics
  - Saab Dynamics
- ***Norway***
  - Kongsberg Aerospace
- ***Taiwan***
  - Hsiung-Feng
- ***Australia***
  - Defense Science & Technology Organisation

DATA SHEET III-16.6. WIDE-AREA IMAGING AND SURVEILLANCE SENSORS

Developing Critical Technology Parameter	In next 5 to 10 years. Imaging sensors will be able to detect targets in shallow hide and camouflage or foliage. Interferometric synthetic aperture radar (IFSAR) sensors will provide rapid production of current and high-resolution terrain data over wide-ranging areas from airborne and spaced-based platforms. Laser radars will produce high-resolution DTED maps (see Section 16.3). Resolution: 1 m at 500 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integrating ATR algorithms and POSITIME systems with sensors.
Technical Issues	Processing the images over very large synthetic apertures (25–45 deg), removal of man-made interferences (communications and television), and target detection in the presence of numerous large clutter signals (tree trunks). Transmission of ultrahigh volume surveillance information.
Major Commercial Applications	Tracking high-value commercial vehicle and rail cargo.
Affordability	Mostly unique military hardware and software that will still rely primarily on government investment. Integration and interoperability are major cost drivers.

RATIONALE

This technology will provide target identification over a wide area of the battlefield, both day and night, and in all weather conditions. Key technologies will focus on the penetration of camouflage and foliage. A new third-generation thermal imaging (TI) camera operating in a 3–5 μm waveband can provide high sensitivity in the detection and tracking of high-temperature target emissions, such as missile plumes and very high velocity airborne threats.[8]

Target identification can be achieved using sound waves. Time-delay spectrometry can be employed as a way of isolating a desired reflected signal from other reflections. This dramatically increases the SNR when a neural-network-based classification system is used. Propagation of sound in the atmosphere is governed by a number of interacting physical mechanisms, including geometrical spreading, molecular absorption, reflection from a porous ground, curved ray paths due to refraction, diffraction by ground topography, and scattering by turbulence. Accurate predictions of sound signatures from a distant source must somehow account for all of these phenomena simultaneously. Although this goal is still beyond current capabilities, developments in computational tools for predicting sound propagation through the atmosphere have increased dramatically during recent years. The computational techniques now include analytical solutions for propagation above porous ground, analytical solutions for selected

8 www.bae.co.uk/static/p3108971.html

atmospheric profiles, ray-tracing techniques which include interaction with the ground and meteorological conditions, and more sophisticated numerical solutions to the wave equation.

The U.S. Army's Foliage Penetration Radar technology development program is focusing on detecting critical mobile targets in shallow hide and camouflage. It is testing an ultra-wide-band system that has the ability of penetrating the foliage canopy and detecting objects on the ground.[9]

The conversion of interferometric synthetic aperture radar (IFSAR) to obtain highly accurate elevation data is possible using innovative algorithms. Near real-time elevation data determination is also possible using fast correlating stereo and high multiple electro-optical images. Laser radars can be used for the production of high-resolution DTED (see Section 16.3)

This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at its longest lethal range. CID technology is a major element of the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

The following technology enhancements should be pursued:

- Low-cost, space-based, multisensor system for both detecting stationary and moving targets, which can be launched on demand
- POSITIME integrated to all imagery and data, providing a common grid reference of the battlespace for theater commanders and intelligence analysts
- Secure ultra-high bandwidth (> 3 GHz) for near-real-time transmission of surveillance and imaging information
- Continuous sensor improvements that can interpret imaging and nonimaging sensor data to reliably identify the target ID in near real time
- Communication improvements in secured data dissemination for SA multimedia information down to the lowest mobile echelon
- A reliable automated decision-aid tool to handle the unprecedented amount of raw information produced by modern sensor systems and by the effectiveness of C3 systems.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Belgium	●	Canada	●●●
China	●	Finland	●	France	●●●	Germany	●●●●
Greece	●	Israel	●●	Italy	●●●	Japan	●
Russia	●●●●	UK	●●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Wide-area surveillance and imaging sensor research is limited to NATO countries, Russia, and China. At present, the United States, Russia, Germany, and the UK appear to be leaders.

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[9] Statement of Honorable P.G. Kaminski before House Permanent Select Committee on Intelligence, October 18, 1995.

The following organizations have active research programs in this technology:

- ***United States***
  - ERIM International
  - Johns Hopkins Applied Physics Lab
  - Naval Research Laboratory
- ***UK***
  - British Aerospace Systems and Equipment
- ***Germany***
  - Daimler-Benz Aerospace, now Dornier GmbH Satellitensysteme
- ***Russia***
  - Institute of Radio Engineering and Electronics at Fryazino

DATA SHEET III-16.6. SYNTHETIC APERATURE RADAR (SAR) AND INVERSE SAR (ISAR) SENSORS

Developing Critical Technology Parameter	Next 5 to 10 years: Recognizing targets under variable sensor and deployment conditions, coping with sensor squint, depression and aspect angles, target articulation, configuration, shadow obscuration, terrain layover, and camouflage. Target mapping in color. Mapping resolution less than 1 ft in both azimuth and slant range. Mapping swath: 10 nmi. Altitude range: 0.2 to 13.1 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Use of model-driven ATR for both SAR and ISAR sensors.
Technical Issues	SAR sensors good for stationary targets. ISAR sensors good for moving targets, but required to be stationary. Need to develop a long-distance multisensor good for both stationary and moving targets, on moving or stationary platforms. Increased resolution of sensors for longer range detection and identification.
Major Commercial Applications	Imaging technologies are used in medical imaging, law enforcement, robotics, transportation sensing, and multimedia. Precision mapping and images.
Affordability	Combining technologies for both stationary and moving targets is a cost driver, but a high operational payback. Integration and interoperability are major cost drivers.

RATIONALE

This technology, when integrated with ATR algorithms and digital map data bases, will provide long-range positive identification using SAR sensors for stationary targets and ISAR sensors for moving targets. SAR/ISAR advantages include all-weather capability, high resolution, and imaging at long distances.

This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at its longest lethal range. CID technology is a major element of the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

Temporal integration (position and time tagging) of information offers a powerful potential for ATR processing. For example, in automatic mine detection, land mines that are placed sufficiently far underground can fall into the "too-hard-to-detect" category. However, if a small collection of vehicles is observed in a particular pattern and that information is stored, later retrieval, after evidence of a mine is determined, can correlate the information of the known mine with the position of the suspicious vehicles to determine location of the remaining mine.

The Defense Advanced Research Projects Agency (DARPA) and U.S. Air Force are developing model-driven ATR technologies for SAR. One of the primary goals of SAR is to develop integrated approaches for recognizing targets under variable sensor and deployment conditions, coping with sensor squint, depression and aspect angles, target articulation, configuration, shadow, obscuration, terrain layover, and camouflage. In the near time frame, it is expected to recognize 20 different high-value tactical and strategic targets under all sensor and deployment conditions.

The following technology enhancements should be pursued:

- Larger storage capacity, rapid retrieval, and faster computing processors for ATR systems
- Long distance multisensors good for detecting both stationary and moving targets on either a moving or stationary platform
- POSITIME integrated to all imagery, providing a common grid reference of the battlespace for theater commanders and intelligence analysts.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Belgium	●	Canada	●●
China	●●	Finland	●	France	●●●	Germany	●●●
Greece	●	Israel	●●●	Italy	●●●	Japan	●●
Norway	●	Russia	●●●	Sweden	●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

SAR and ISAR research is being carried mainly by universities and countries involved in space research (i.e., European Space Agency, Canadian Space Agency, and NASA). At present, the United States appears to be the leader.

The following organizations have active research programs:

- ***United States***
  - Boeing
  - General Atomics
  - Heriot-Watt University
  - Johns Hopkins University
  - Joint Propulsion Laboratory
  - Lockheed Martin
  - NASA
  - Ohio State University (Electro Science Laboratory)
  - Raytheon
  - Sandia National Laboratories
  - TRW
  - Yale University
- ***UK***
  - AEL University of Dundee
- ***Germany***
  - Daimler Chrysler Aerospace
  - DLR
  - FGAN
- ***France***
  - Alcatel

- ***Italy***
  - Universita’ di Pisa
- ***China***
  - IEAS
- ***Canada***
  - Canadian Space Agency
- ***Russia***
  - Institute of Radio Engineering and Electronics
  - VEGA-M Scientific and Production Corporation
  - Russian Academy of Sciences

DATA SHEET III-16.6. INFRARED SENSORS/DEVICES

Developing Critical Technology Parameter	Next 5 to 10 years: This technology will provide a day/night target detection, classification, and dissemination capability at stand-off ranges. Can identify noncooperative, small-radar-cross-section aircraft, ground vehicles, and ships at extended ranges. Range expected to increase 3–5× from current capabilities.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Target classification systems is required.
Technical Issues	Positive identification on noncooperative air and ground targets need to be addressed.
Major Commercial Applications	Law enforcement agency use for interdiction, boarding, and surveillance. Automatic highway systems.
Affordability	Complexity of classification signature data base and integration are major cost drivers. Integration and interoperability are major cost drivers.

RATIONALE

This technology provides day/night target detection and relative distance and velocity of target. Integrated with ATR software it can identify target classification at standoff ranges. Infrared cameras can be used to detect shallowly buried or surface landmines. Other applications vary, from use as night vision and thermal image sensors, to use as an airborne FLIR system that can identify noncooperative aircraft, ground vehicles, and ships at extended ranges. The FLIR sensor performs unresolved target detection and handoff to the laser radar for target exploitation. Targets are interrogated to generate classification signatures by exploiting the return signal from the target. It can then transmit near-real-time target signature and high-resolution imagery to operational theater commanders via wideband satellite links.

Infrared devices can be used for signaling and marking, providing an inexpensive means of identification. Such devices include thermal tapes, BUDD lights, and a codeable infrared beacon (i.e., Phoenix light) with a range of 4 km, but with the advantage of reprogramming codes to distinguish within a group. Combining the advantage of night vision goggles (that can pick up visual light sources at large ranges) and IR sensors (that are not susceptible to strong light sources and can work in total darkness) can provide improved situational awareness in urban warfare.

This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at their longest lethal range.

CID technology is a major element of the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release. The Joint Surveillance/Intelligence plan also identifies this technology as a means to address positive identification of noncooperative targets.

The enhancement to integrate POSITIME to all imagery, providing a common grid reference of the battlespace for theater commanders and intelligence analysts, needs to be pursued.

Current sensors can discriminate for positive identification at ranges up to about 5 km. By 2025 this range could increase by an order of magnitude, and pattern-recognition logic could assist in threat determination by observing discriminators such as vehicle type, color, and motion, or observations that personnel were carrying weapons and moving in a tactical manner.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Belgium	●	Canada	●●●
China	●	Finland	●	France	●●●	Germany	●●●
Greece	●	Israel	●●	Italy	●●	Japan	●
Russia	●●	UK	●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Infrared research is being carried out throughout the industrialized world. At the present time, the United States appears to be the leader.

The following organizations have active research programs:

- ***United States***
  - Boeing
  - DRS Optronics
  - Epitaxial Technologies (University of Maryland)
  - FLIR Systems
  - Honeywell
  - Laser Devices, Inc.
  - Lockheed Martin
  - Northrop-Grumman
  - Raytheon
  - Tracer Technology
- ***France***
  - Société Francaise de Detecteurs Infra Rouge
- ***Germany***
  - Diehl-Aerospace
- ***Canada***
  - The National Optics Institute

DATA SHEET III-16.6. LASER RADAR SENSORS/DEVICES

Developing Critical Technology Parameter	In next 5 to 10 years: Three-dimensional laser radar with tunable laser radar for target detection and identification of obscured targets. Wavelength: 1.5 µm to 3.5 µm. Ground-to-ground: measure the shape of objects at distances of 1 km or more. Can display the shape and directional velocity of moving targets. Range data is measured to an accuracy of 0.005 m. Air to ground: determine target location with accuracy of 0.3 m from 40,000 ft.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integrates GPS, ATR software, and satellite communications.
Technical Issues	Detecting targets in shallow hide and camouflage or foliage.
Major Commercial Applications	Vehicle detection and classification as part of intelligent highway systems; automation of agricultural equipment and precise measurement of distances.
Affordability	Integration and interoperability are major cost drivers.

RATIONALE

This technology will allow warfighter to rapidly detect, identify, and locate target position within 1-m accuracy and transmit data/imagery to other users. Laser radar and rangefinders can detect and precisely measure the position and velocity of ground and air vehicles. Integrated with a miniature IFF interrogator ATR algorithm, laser radar and rangefinders can provide validated target identification and classification validation of friendly forces, as well as enemy and neutrals. Laser technologies have a wide diversity of military applications, including rangefinders, LPI altimeters, and LPI terrain-avoidance sensors. Laser radar systems can search for specific shapes by ATR algorithm. In this case the analysis is done automatically, and the operator is alerted when target is identified. Laser camera systems can generate complete three-dimensional images of the field of view, particularly for long ranges over 1,000 m in distance.

This technology supports the Joint Vision 2010 goals of dominant maneuver and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at their longest lethal range. CID technology is a major element of the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

The U.S. Air Force's Spacecast 2020 study suggested an exotic, space-based target-recognition scheme in which a laser beam from a satellite would scan the battlefield, and sensors on the spacecraft would analyze the reflected energy. By comparing the spectra, identification would be possible. Friendly tanks and aircraft could be chemically coated to produce a characteristic spectrum when excited by the space-based laser, providing another degree of IFF capability.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Austria	●	Belgium	●	Canada	●●●
China	●●	Finland	●●	France	●●●	Germany	●●●●
Greece	●	Israel	●●●	Italy	●●●	Japan	●●●
Norway	●●	Russia	●●●●	Spain	●	Sweden	●●
Switzerland	●●	UK	●●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Laser radar research is being carried out throughout the industrialized world. At the present time, the United States, Russia, the UK, and Germany appear to be the leaders.

The following organizations have active research programs:

- ***United States***
  - Coherent Technologies Incorporated
  - Fibertek Incorporated
  - Hughes Radar
  - Los Alamos National Laboratory
  - NASA Ames Research
  - Naval Surface Warfare Center
  - Schwartz-Electro Optics
- ***Germany***
  - Fraunhofer Institute for Laser Technology
  - Molecular Technology GmbH
  - University of Worzburg
- ***Russia***
  - Ioffe Physico Technical Institute
  - Institute Atmospheric Optics
  - Lebedev Physical Institute
  - Novosibirsk State University, Laboratory of Laser Systems
- ***UK***
  - AG Electro-Optics
  - British Aerospace Systems & Equipment Incorporated
  - Instruments SA
- ***France***
  - CNRS Ecole Polytechnique;
- ***Finland***
  - Academy of Finland
- ***Sweden***
  - Photonics Research Laboratory
  - Laseroptronix
- ***Japan***
  - Mitsubishi Incorporated
  - National Space Development Agency
  - Nippon Laser & Electronics Laboratory
- ***Canada***
  - Imago Machine Vision, Ltd.
  - York University
- ***China***
  - Ahhui Institute of Optics and Fine Mechanics

DATA SHEET III-16.6. TAGGING TECHNOLOGY

Developing Critical Technology Parameter	In next 5 to 10 years: A micro-silicon chip, no bigger than a coffee grind and a micro-miniaturized antenna will provide a very low-cost ID for installation on any type of material. Tag remains passive until scanned by device (i.e., radio, laser) without having to get near the tag or even have line of sight to it. Transmission can use low probability of intercept algorithms. Scanner can change or add information on the chip.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Low power tag receivers (< 30 mW) and miniature battery (< 0.5 kg) to enable continuos performance for months. Material that when removed from soldier or combat vehicles will render tag useless in case of capture by enemy. LPI/LPD and other security issues. Very low cost requirement for use by all personnel and assets, particularly in a combat urban area.
Major Commercial Applications	Replacement for bar codes. Tracking mail, luggage, production parts and spare parts, identification and location.
Affordability	Leveraging commercial technology will minimize cost.

RATIONALE

Tags can be used actively or passively to provide vehicles and personnel tracking on which those tags have been implanted, overtly or covertly. The tags can be implanted in equipment upon manufacturing, into raw materials at growth or mining, or onto vehicles, and equipment later (i.e., decals). The location or activity could be scanned from ground or overhead (i.e., UAV or satellite) radio or laser scanners.

Use of microminiature RFID tags could provide a low-cost real time beyond line-of-sight positive identification of personnel and combat assets within the local battlefield area, especially in urban terrain environments.

This technology supports the Joint Vision 2010 goals of dominant maneuver, and precision engagement by providing a clearer picture of enemy and friendly locations in the battlespace. Knowledge of the precise location of dispersed friendly forces and enemy forces will enhance standoff capabilities of weapons at its longest lethal range. CID technology is a major element of the Joint Warfighting S&T Plan to differentiate potential targets as friend, foe, or neutral in sufficient time, with high confidence, and at the requisite range to support engagement decisions and weapon release.

DARPA is currently developing an RF tag technology to allow airborne radar (both moving target indication and SAR) to communicate directly with ground devices to provide identification of friendly assets, to communicate information directly from ground sensors to the platform, and to correct for errors in the radar-determined location of targets. This may resolve a technical barrier of obtaining target identification using radar data alone. This is especially true in conflicts where a mix of friendly, unfriendly, and neutral forces will be mixed with non-combatants.

This technology is in its infancy for combat identification applications, and therefore should continue to be pursued to provide micro-miniature transponding tags with data storage and LPI/D transmission capability which is suitable for long-range military operations.

There are no special requirements for the U.S. Government to gain access to this technology. The substantial margin of capability added is critical to continued U.S. superiority in SA and the multitude of missions dependent thereupon.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●●	Austria	●●	Belgium	●	Canada	●●●
China	●	Finland	●	France	●●	Germany	●●
Greece	●	Israel	●●	Italy	●●	Japan	●
Netherlands	●●	Russia	●	South Africa	●●	Sweden	●●
Switzerland	●	UK	●●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Commercial interests are advancing the development and production of this technology. At present, it appears that the United States, Canada, and the UK are leading in the development of low-cost RFID tagging technology for commercial applications. This is an emerging technology for military applications.

The following organizations are active in this technology:

- ***United States***
  - AMTECH
  - Avid Inc.
  - BasIQ Systems
  - Beigel Technology Corporation
  - Biomark
  - DARPA
  - ERIM International Inc.
  - Escort Memory Systems
  - Microchip Technology
  - Motorola
  - RF Technologies
  - Southwest Research Institute
  - Toyon Research Corporation
- ***Canada***
  - Identec Solutions, Inc.
  - Kasten Chase Applied Research, Ltd.
  - RFID Systems Corporation
  - SAMSys Technologies Inc.
- ***Australia***
  - Amskan
  - Integrated Silicon Design
- ***Austria***
  - Philips Semiconductors Gratkorn GmbH
- ***UK***
  - A.P.T. Smart Solutions
  - IB Technology, Ltd.
- ***France***
  - Balogh

- ***Sweden***
  - Baumer Iden AB
  - Tagmaster AB
- ***Germany***
  - DIEHL Ident GmbH
  - Scemtec
  - Siemens AG
- ***Italy***
  - Extel srl
- ***South Africa***
  - Infotronics
- ***Israel***
  - Tadian Telematics, Ltd.
- ***Netherlands***
  - Cross Point b.v.
  - TNO Institute of Applied Physics
- ***Switzerland***
  - EM Microelectronic-Marin SA